



BIOMASS AND REMOTE SENSING OF BIOMASS

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INTECH

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Published by InTech

Janeza Trdine 9, 51000 Rijeka, Croatia

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Publishing Process Manager Niksa Mandic

Technical Editor Teodora Smiljanic

Cover Designer Jan Hyrat

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First published August, 2011

Printed in Croatia

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Biomass and Remote Sensing of Biomass, Edited by Islam Atazadeh

p. cm.

ISBN 978-953-307-490-0

Carbon Storage in Cold Temperate Ecosystems in Southern Patagonia, Argentina

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1. Introduction

Recently there has been an increasing interest of research related to improve the understanding of carbon (C) sequestration mainly under Article 3.4 of the Kyoto Protocol of the United Nations Framework Convention on Climate Change where countries can count this sequestration as a contribution to reduce greenhouse gas emission (IPCC, 2001). Data on C storage in forests, grasslands and shrublands are essential for understanding the importance of rapidly increasing level of CO₂ in the atmosphere and its potential effect on global climate change. In South America, mean annual temperature is predicted to increase by 3-4 °C in both summer and winter between 30° and 55° SL (Manabe & Wetherald, 1987). Such an increase would have significant effects on Patagonian ecosystems. In this context, secondary indigenous forests are considered efficient C sink ecosystems. *Nothofagus antarctica* (ñire), one of the main deciduous native species in the Patagonian region (Argentina), covers 751.643 hectares over a wide latitudinal (from 36° 25' to 54° 53' SL) and altitudinal (near sea level to 2000 m.a.s.l.) distribution. These forests occur naturally in different habitats such as poorly drained sites at low elevations, exposed windy areas with shallow soils, depressions under cold air influence, or in drier eastern sites near the Patagonian steppe (Veblen et al., 1996). These forests provide a range of wood products including poles, firewood and timber for rural construction purposes. Site quality for *N. antarctica* ranges from tall trees up to 15 m in dominant height on the best sites to shrubby trees of 2 m tall on rocky, xeric and exposed sites, and also in poorly drained sites. Previous research has highlighted the importance of stand age on the magnitude of C pools in both forest biomass and forest floor pools (Silvester & Orchard, 1999; Davis et al., 2003). Large-scale canopy disturbance in *N. antarctica* forests may occur as a result of blowdown, snow avalanches or fire. This results in abundant regeneration (100,000 seedlings ha⁻¹ less than 1 m tall, up to 20 years of age) followed by self thinning due mainly to light competition resulting in a final stand density of 200-350 trees ha⁻¹ at mature stages (more than 180 years of age). It is important to emphasize that many researchers have only focused on above-ground carbon sequestration (Davis et al., 2003). However, roots in forest ecosystems can contribute up to two times more biomass than above-ground components in young growth phases (Peri et al., 2006, 2008). There are few studies of above- and below-ground pools of C

storage in Patagonian *Nothofagus* forests that provide an understanding about ecosystem functionality (Peri et al., 2004, 2005) and the consequences of different disturbance and management regimes. In this context, forest ecosystem pools and fluxes of C are strongly affected by forest management (Finér et al., 2003). Peri et al. (2010) showed that C storage in tree components (leaves, stems, branches, roots) and forest floor change as a result of different forest structure determined by the proportion of crown classes, development stages (age) and the site quality where trees grow.

The steppe ecosystem, mainly characterised by the presence of tussock, short grasses and shrubs, covers 85% of the total area. Grazing has modified the structure of Patagonian ecosystems by reducing vegetation cover, increasing bare areas, and changing floristic composition. Erosion and degradation processes have occurred in several areas of Patagonia due to an overestimation of the carrying capacity of these rangelands, inadequate distribution of animals in very large and heterogeneous paddocks, and year-long continuous grazing (Golluscio et al., 1998). In Patagonia, most of the actual knowledge about the environmental factors that affect net primary production of grasslands at regional level derives from the importance of mean annual precipitation, radiation and temperature (Jobbágy & Sala, 2000). However, data on C accumulation in both above- and belowground components of plant functional types are essential for evaluating the impacts of grazing on C cycle and long-term effects on the C balance of grasslands. Global estimates of the relative amounts of C in different vegetation types suggest that grasslands approximately contribute more than 10% of the total biosphere store (Nosberger et al., 2000). Also, it has been demonstrated that most temperate grasslands under existing management conditions are considered to be C sink and sequester more C than arable crops (Connan et al., 2001).

Therefore, the aim of this manuscript was to describe the amount of C in both above- and below-ground components for the main cold temperate ecosystems in Southern Patagonia (Argentina). In particular, the aim was to quantify the C storage in an age sequence and among crown classes for individual trees grown at different site qualities of deciduous *N. antarctica* forests in Southern Patagonia and under silvopastoral use, and to quantify the amount of C for main grassland steppe ecosystems including the effect of grazing.

2. Carbon storage in main Patagonian ecosystems

2.1 *Nothofagus antarctica* native forest

Above- and below-ground C pools were measured in pure even-aged stands of *Nothofagus antarctica* at different ages (5 to 220 years), crown (dominant, codominant, intermediate, suppressed) and site (site class III (SC III) where the mean total height of dominant mature tree (H) reached 10.2 m, site class IV (SC IV) where H reached 7.8 m, and site class V (SC V) which represented a marginal site where H reached 5.3 m) classes in the Patagonian region (Peri et al., 2010). Mean tissue C concentration varied from 46.3% in medium sized roots of dominant trees to 56.1% in rotten wood for trees grown in low quality sites. Total C concentration was in the order of: heartwood > rotten wood > sapwood > bark > small branches > coarse roots > leaves > medium roots > fine roots.

Sigmoid functions were fitted for total C accumulation and C root/shoot ratio of individual trees against age for each site class. The parameters are given in Peri et al. (2010). Total C accumulation over time followed the order: dominant > codominant > intermediate > suppressed trees (Fig. 1a). For example, dominant trees growing on SC III had accumulated 228 kg C tree⁻¹ after 180 years and suppressed trees only 46 kg C tree⁻¹. Also, site quality of

the stands had a strong impact on total C accumulation over time. For example, while the mean total C accumulated for dominant trees grown in SC V at 150 years was 109 kg C tree⁻¹, dominant trees growing on SC III had 207 kg C tree⁻¹. C accumulation was divided by tree age to establish the average annual rate at which C was accumulated by trees. The rate of C accumulation showed a parabolic relationship with tree age and increased to reach a maximum and then declined as tree age increased further (Fig. 1b). Crown class also affected the maximum value and shape of this response. For example, maximum accumulation rate for dominant trees growing on SC III was 1.44 kg C tree⁻¹ year⁻¹ at 116 years and then declined to 1.10 kg C tree⁻¹ year⁻¹ at 220 years (Fig. 1b). In contrast, maximum accumulation rate for suppressed trees was 0.26 kg C tree⁻¹ year⁻¹ at 139 years (Fig. 1b). Also, the site quality modified the maximum values and the shape of the rate of C accumulation. The greater C accumulation of dominant trees at any age compared to inferior crown classes was very closely related to the C accumulation rates. This is consistent with Rötzer et al. (2009) who estimated that the amount of C storage in both above- and belowground components over time for a mixed beech stand changed with variations in site conditions, especially when precipitation decreased. Dominant trees and trees growing in better site qualities had larger crowns with more biomass of photosynthetic green leaves, and consequently had faster growth rates. In contrast, the leaves of suppressed trees located in the inferior stratum receive less available light for photosynthesis and these less active leaves may accumulate less C. For *N. antarctica* trees, there were no significant difference in the slope of the relationship between the C root/shoot ratio and age for different crown classes. Therefore, a single function was used for each site quality class. C root/shoot ratio decreased with age from a maximum value to a steady-state asymptote value. For example, C root/shoot ratio decreased from maximum values of 1.3 at 5 years to a steady-state asymptote of 0.3 beyond 60 years of age, for trees grown in SC III (Fig. 1c). Thus, root C accumulation was greater during the regeneration phase, and then the above-ground C accumulation of young and mature trees increased over time. The above-ground C content for *N. antarctica* was lower than values reported by Hart et al. (2003) for an even-aged *N. truncata* old growth forest (root/shoot ratio of 0.28). At any time, the root C accumulation was greater for trees growing on the poorer sites (SC V) than for better site conditions. It has been demonstrated that *N. antarctica* has more root biomass to ensure establishment during stand replacement to improve water and nutrient uptake in dry environments and to provide better support in windy sites with shallow soils, compared to other *Nothofagus* species (Gargaglione et al., 2010).

In primary *N. antarctica* forest there were no significant differences in soil C pools for different age classes (data not shown). This is consistent with Davis et al. (2003) who reported that the sum of forest floor and mineral soil C in a New Zealand *Nothofagus* forest did not differ with age. However, total C content in the soil profile varied according to the site quality from 87.7 to 198.8 Mg C ha⁻¹ for SC V and SC III, respectively (Table 1). Soil C concentration increased from SC V to SC III thus influencing C content in organic and inorganic horizons (Table 1). The C content of litter, organic-layer and inorganic soil layers were greater in the best site quality class stands. The C in the soil pool (Table 1) represents between 52% (optimal growth phase stand grown at SC IV) and 73% (mature phase stand grown at SC III) of total ecosystem C. The soil C pool estimated in the present work was greater than those reported for other *Nothofagus* species (Tate et al., 1993; Hart et al., 2003) and similar to native cypress forests in Patagonia (Laclau, 2003). This highlights the importance to quantify the variability in soil C storage among forest types.

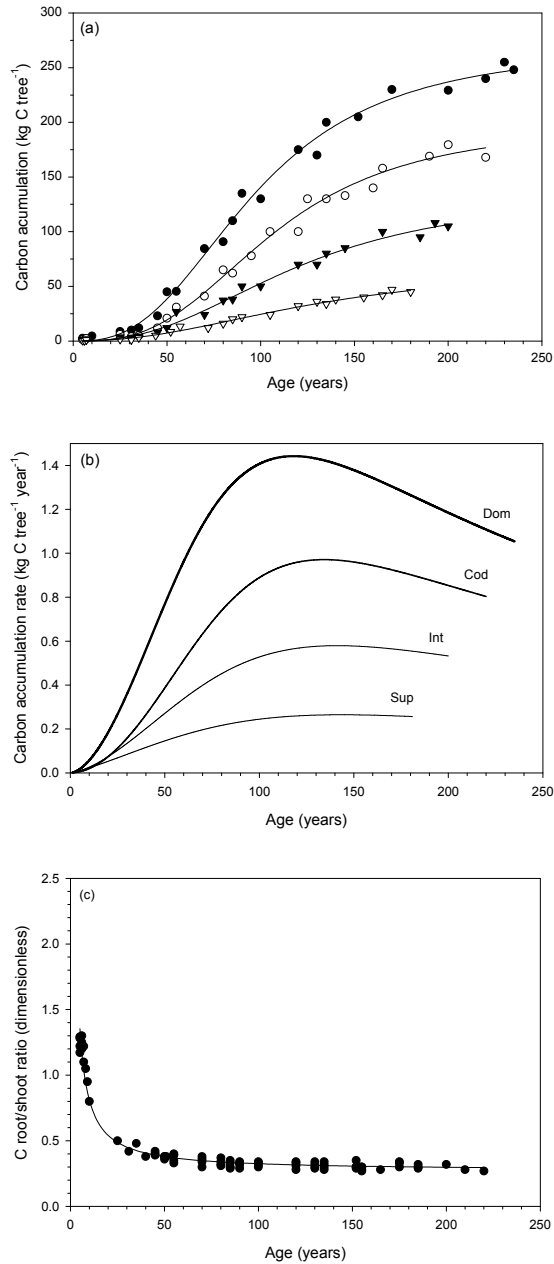


Fig. 1. Total carbon (C) accumulation (a), C accumulation rates (b) and C root/shoot ratio (c) against age for different crown classes of *N. antarctica* trees growing at Site Class III (mean total height of dominant mature tree 10.2 m) in south Patagonia, Argentina (Peri et al., 2010).

The equations for total C accumulation from individual trees were used to estimate the C storage at the stand level using forest inventory data. Total C storage in *N. antarctica* forest ranged from 40.3 Mg C ha⁻¹ for mature stands grown at SC V to 182.0 Mg C ha⁻¹ for optimal growth stands at SC III (Table 1). In all studied site quality classes, total C accumulation was greater at the development stage of optimal growth (21-110 years). Similarly, Davis et al. (2003) estimated that stem C storage in *N. solandri* var. *cliffortiodes* forest in a montane zone of New Zealand reached a maximum value (137 Mg C ha⁻¹) at the pole development stage (120 years). In contrast, Laclau (2003) reported that C storage of native cypress forest in northwest Patagonia did not change significantly with stand age and precipitation (site quality). Sapwood contained more C in SC III (66.4 Mg C ha⁻¹) than SC IV (32.5 Mg C ha⁻¹), while medium roots contained more C in the SC V (15.8 Mg C ha⁻¹) stands. In particular, roots accounted for 26% (regeneration phase grown at SC III) to 72% (mature phase grown at SC V) of total C in living trees of the stands (Table 1). In contrast, Hart et al. (2003) showed that mature *N. truncata* forest growing on a better site quality (dominant height of 21 m) had greater amounts of C in the above- than the belowground components (166 vs. 47 Mg C ha⁻¹).

Soil horizons	Site Class III				Site Class IV				Site Class V			
	Litter	Organic Horizon	Mineral Horizon I	Mineral Horizon II	Litter	Organic Horizon	Mineral Horizon I	Mineral Horizon II	Litter	Organic Horizon	Mineral Horizon I	Mineral Horizon II
Depth (cm)	0-2	2-6	6-20	20-60	0-1	1-5	5-30	30-60	0-1	1-4	4-20	20-50
Bulk density (g cm ⁻³)	0.07	0.47	0.79	1.04	0.10	0.39	1.14	1.29	0.09	0.63	0.97	1.05
Carbon concentration (%)	47.2	16.0	6.0	2.3	50.8	14.2	2.1	0.4	49.1	9.4	3.2	0.5
Carbon content (Mg ha ⁻¹)	6.6	30.1	66.4	95.7	5.8	22.1	59.8	15.5	4.4	17.8	49.7	15.8

Stand	Leaves	Small branches	Sapwood	Heartwood	Bark	Rotten wood	Roots <2mm	Roots <30mm	Roots >30mm	Total
<i>Site Class III</i>										
Regeneration	4.6	9.6	48.3	28.5	15.7	5.4	1.1	5.4	33.4	152.1
Optimal growth	11.9	21.8	66.4	9.6	16.3	0.0	3.0	17.2	35.7	182.0
Mature	4.5	13.9	12.0	0.0	3.2	0.0	1.7	26.4	13.5	75.1
<i>Site Class IV</i>										
Regeneration	0.8	2.0	13.4	14.6	7.2	1.0	0.3	2.6	14.2	56.2
Optimal growth	3.6	7.3	32.5	5.9	9.3	0.0	0.9	8.9	19.4	87.9
Mature	2.9	8.6	7.1	0.0	2.5	0.0	3.0	24.6	9.9	58.6
<i>Site Class V</i>										
Regeneration	0.8	2.1	8.4	13.2	4.6	1.7	0.1	2.8	16.6	50.3
Optimal growth	1.9	5.7	13.1	3.0	4.6	0.5	1.5	8.0	15.8	54.0
Mature	1.1	5.2	4.1	0.0	1.9	0.0	3.4	16.5	8.2	40.3

Table 1. Mean soil carbon content and predicted amount of carbon (Mg C ha⁻¹) in sampled *Nothofagus antarctica* stands in Southern Patagonia (Peri et al., 2010). Site Class III: stands where the mean total height of dominant mature tree (H) reach 10.2 m, Site Class IV: H= 7.8 m, Site Class V: H= 5.3 m

2.2 Silvopastoral systems

Deciduous *N. antarctica* forest has been usually used as silvopastoral systems (trees growing with natural pastures in the same unit of land to feed cattle and sheep). These forests are

considered efficient carbon (C) sink ecosystems. Peri et al. (2009) reported the aboveground and belowground C sequestration for different components of trees and pasture (green and dead leaves, pseudostem and coarse and fine roots), and the C storage in litter floor and different horizons of mineral soil (from 0 to 0.6 m depth) in a *N. antarctica* silvopastoral system grown in Southern Patagonia at a site class IV (SC IV) where H reached 7.8 m. Mean stand density was 180 trees ha⁻¹ (78% dominant trees and 22% codominant trees) in mature development stage (196 years). In this ecosystem, the C concentration was higher in the tree component of rot (55.3%) and lower in the dead leaves component of pasture (40.5%). The C concentration decreased from 46.9% in floor litter to 2.5% at 0.6 m mineral soil depth. At the silvopastoral stand level, the total C stored was 252 Mg C ha⁻¹ distributed 86.7% in soil, 11.9% in trees and 1.4% in pasture (Table 2). Belowground biomass represented an important C storage pool in the ecosystem with mean values of 8.9 and 2.6 Mg C ha⁻¹ for trees and pasture roots components, respectively. Total C accumulation in trees (30.1 Mg C ha⁻¹) followed the order heartwood > coarse roots > sapwood > bark > small branches > rot > leaves > fine roots. C storage in litter floor was 7.4 Mg C ha⁻¹, and in the mineral soil ranged from 13.6 Mg C ha⁻¹ (horizon 0-0.03 m depth) to 98.6 Mg C ha⁻¹ (horizon 0.30-0.60 m depth). This is consistent with Dixon et al. (1994) who reported that the potential carbon storage with agroforestry systems in temperate zones ranges from 15 to 198 Mg C ha⁻¹. Sharrow & Imail (2004) stated that silvopastoral system in Oregon (United States) were more efficient in C sequestration due to the higher biomass production and active nutrient cycling

System component	Mg C ha ⁻¹
<i>Soil</i>	
Litter	7.4
Organic horizon (0-03 m)	13.6
Mineral horizon (0.03-0.10 m)	17.6
Mineral horizon (0.10-0.30 m)	81.3
Mineral horizon (0.30-0.60 m)	98.6
<i>Total soil</i>	218.5
<i>Trees</i>	
Leaves	0.5
Small branches	1.0
Sapwood	7.3
Heartwood	8.2
Bark	3.7
Rot	0.5
Fine roots	0.1
Coarse roots	8.7
<i>Total trees</i>	30.1
<i>Pasture</i>	
Green leaves	0.5
Dead leaves	0.1
Pseudostem	0.4
Roots	2.5
<i>Total pasture</i>	3.5
<i>Total silvopastoral system</i>	252

Table 2. Mean carbon storage of different components of a typical *Nothofagus antarctica* silvopastoral system in Southern Patagonia (Peri et al., 2009)

patterns compared with tree plantations or pasture monocultures. This study improved the understanding about the potential of C sequestration of *N. antarctica* forests under silvopastoral management and highlights the importance of these forests as efficient carbon sink ecosystems.

2.3 Shrubland

In Santa Cruz province there is a "matorral" thicket area dominated mainly by *Junellia tridens* covering 2.8 million hectares among the grasslands of the Magellanic steppe and the steppe of the Central Plateau (Borrelli et al. 1997). These communities grow on sites with coarser-textured soils, are dominated by 60-70 cm tall shrubs. Water is the most important factor regulating primary production. Shrublands constitute significant and important parts of southern Patagonian landscapes providing a large number of important ecosystem services. Biogeochemical cycles in these ecosystems have gained little attention relative to forests and grassland systems. Our primary intent was to create dimensional relationships between two easily measured plant properties, crown area and height, and the total biomass and C for the major shrub species. From this, significant differences were detected in total below- above-ground shrub C, estimated by applying species specific models to the shrub dimensional data sets (Fig. 2). The relative proportion of C has been constituted by the major species varied with stand age and *J. tridens* shrub cover. Total plant C varied from 4.4 to 12.5 Mg C ha⁻¹ for 20 and 60% shrub cover, respectively (Fig. 2). In this ecosystem, the C root/shoot ratio ranged between 0.17 and 0.30. The soil carbon store (0-30 cm) dominates the carbon

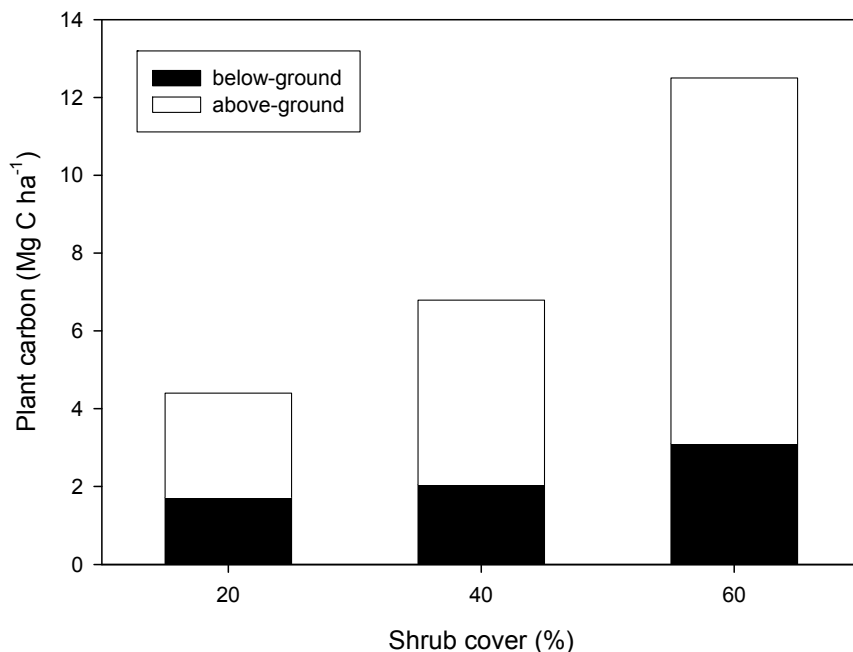


Fig. 2. Total plant carbon (C) accumulation for different shrub cover of "matorral" thicket area dominated mainly by *Junellia tridens*, Santa Cruz province

budget at all *J. tridens* shrubland sites and ranged from 70 (for 10-20% shrub cover) to 160 Mg C ha⁻¹ (for 60-70% shrub cover) where soil C constitutes more than 90% of the total carbon in the ecosystem. This is consistent with Beier et al. (2009) who reported that soil C constitutes 95% of the total carbon in six shrublands along a climatic gradient across the European continent.

2.4 Grasslands

The Magellanic Patagonian steppe (southern Patagonia, Argentina) is a cold semiarid environment characterized by strong winds and high evaporation rates that cover 3 million hectares where grasses and shrubs are the dominated plant functional types with contrasting root systems. In this ecosystem *Stipa chrysophylla* and *Festuca pallescens* are dominant tussock species commonly associated with cool season *Poa dusenii* and *Carex andina* short grasses (Roig et al., 1985). There are antecedents related to biomass and C storage in the Patagonian steppe for main tussocks, short grasses and dwarf-shrub species (Peri & Lasagno, 2006, 2008, 2009, 2010). In this ecosystem, C concentrations varied according to tissue components in all species studied, plant size and growing season being higher in coarse roots and green leaves. Total accumulation of C per hectare for three different grassland species composition and cover is presented in Table 3. Total carbon accumulated from grass plants ranged from 4.9 to 17.7 Mg C ha⁻¹ depending on the main dominant species (Table 3). The greatest C accumulation of dominant *F. pallescens* grassland was mainly due to differences in biomass accumulation rates and to larger crowns with more biomass (Peri & Lasagno, 2010). Carbon distribution between components varied according to the grassland composition. Thus, while dominant *S. chrysophylla* grassland accumulated more C in the senesced leaves component (2.8 Mg C ha⁻¹), dominant *F. pallescens* grassland accumulated more carbon in fine roots (5.2 Mg C ha⁻¹) and dominant *P. dusenii* in coarse roots (1.6 Mg C ha⁻¹) (Table 3). Total C in roots ranged from 2.4 kg Mg C ha⁻¹ for the *P. dusenii* grass steppe ecosystem to 8.7 Mg C ha⁻¹ in the dominant grass riparian *F. pallescens* grassland, representing 49% of total C sequestered by plants. The total C stored in the studied grasslands ecosystems was 222.9 Mg C ha⁻¹ distributed 88% in soil for grass riparian *F. pallescens* grassland and 83.9 Mg C ha⁻¹ distributed 94% in soil. This is consistent with Hungate et al. (1997) who reported that up to 98% of C sequestration in grassland ecosystems occurred belowground and with Reeder & Schuman (2002) who reported that the 80-90% of plant C short-grass steppe was stored belowground in the central Great Plains of USA.

The effect of long-term livestock grazing on C content of the plant-soil grassland system (to 30 cm) of Dry Magellanic Grass Steppe and Sub-andean Grassland areas is presented in Figure 3. The vegetation of the steppe is dominated by grasses and sedges (*Bromus*, *Carex*, *Festuca gracillima*, *Hordeum*, *Jarava*, *Poa*, *Rytidosperma virescens*, *Trisetum*) with dwarf shrubs and herbs such as *Nardophyllum*, *Perezia*, *Azorella*, and *Nassauvia* admixed. The vegetation of the grass-shrub steppe is dominated by *Agrostis*, *Festuca*, *Hordeum* and *Trisetum*, however shrubs (*Adesmia*, *Chuquiraga*, *Junellia*, *Mulinum*, *Senecio*) are also frequent. The carrying capacity (ewe ha⁻¹ yr⁻¹) estimation is based on the biomass production of short grasses and forbs that grow in the space among tussocks of this ecological area and the requirements of 530 kg DM yr⁻¹ for 1 Corriedale ewe of 49 kg of live weight. The baseline corresponds to an undisturbed vegetation area (non grazed areas).

Pool	1. Grass steppe with 65% <i>S. chrysophylla</i>, 3% <i>P. dusenii</i>, 1% <i>F. pallescens</i> and 1% <i>C. andina</i>
Green leaves	2.50
Senesced leaves	2.84
Pseudostem	1.48
Fine roots	2.38
Coarse roots	2.25
Soil (0-0.30 m)	86.1
<i>Total</i>	97.55
	2. Grass riparian with 70% <i>F. pallescens</i>
Green leaves	2.92
Senesced leaves	4.38
Pseudostem	1.73
Fine roots	5.17
Coarse roots	3.49
Soil (0-0.30 m)	205.2
<i>Total</i>	222.89
	3. Grass steppe with 40% <i>P. dusenii</i>, 15% <i>C. andina</i> and 10% <i>S. chrysophylla</i>
Green leaves	0.81
Senesced leaves	0.76
Pseudostem	0.98
Fine roots	0.79
Coarse roots	1.63
Soil (0-0.30 m)	78.9
<i>Total</i>	83.87

Table 3. Carbon amount at stand level (Mg C ha⁻¹) for different steppe grassland composition stands in southern Patagonia (Peri & Lasagno, 2009)

On these extensively managed grasslands, grazing intensity was the main management practices that affected ecosystem C levels. This varied from 50 Mg C ha⁻¹ at a heavy stocking rate (0.70 ewe ha⁻¹ yr⁻¹) to 130 Mg C ha⁻¹ under low grazing intensity (0.10 ewe ha⁻¹ yr⁻¹) (Fig. 3). A slightly higher total C content was detected in the low grazing intensity (0.10 ewe ha⁻¹ yr⁻¹) grassland compared with the non grazed areas (130 vs. 120 Mg C ha⁻¹). This is consistent with Reeder & Schuman (2002) who reported that soil C content was highest in US mixed-grass and short-grass rangelands under grazing, while non-grazed enclosures caused immobilization of C in excessive above-ground plant litter. From a low grazing intensity of 0.10 ewe ha⁻¹ yr⁻¹, total grassland C declined as grazing intensity increased by reaching a value of 103 Mg C ha⁻¹ at a medium stocking rate of 0.35 ewe ha⁻¹ yr⁻¹ (Fig. 3). Then, total grassland ecosystem C was followed by a further decline to the lowest estimated C value. For Dry Magellanic Grass Steppe grassland under sheep grazing, this response showed that 0.35 ewe ha⁻¹ yr⁻¹ stocking rate was a critical value below which ecosystem C was severely restricted. The effect of sheep on system C arose from the influence of grazing

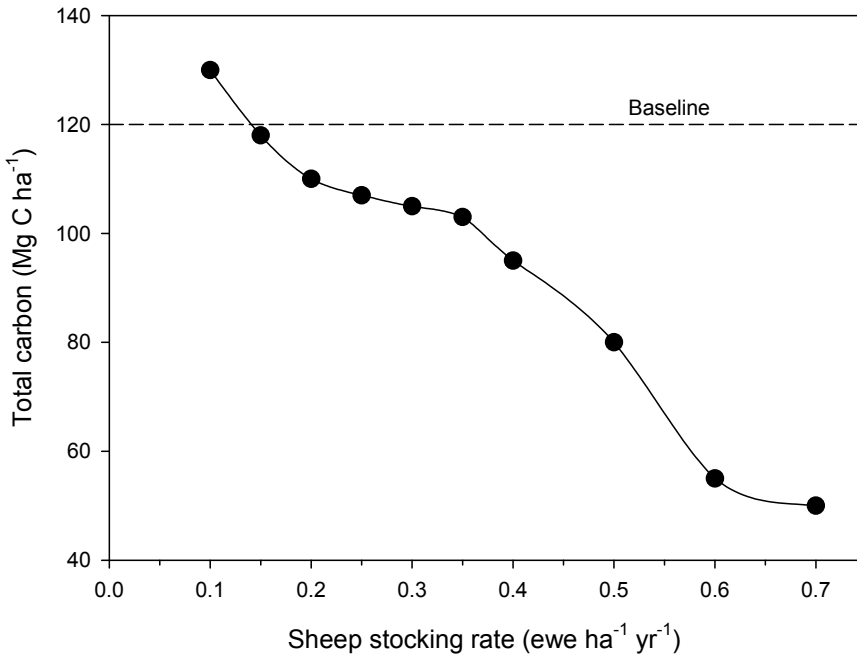


Fig. 3. Effect of long-term livestock grazing on C content of the plant-soil grassland system (to 30 cm) of Dry Magellanic Grass Steppe and Sub-andean Grassland areas, Patagonia, Argentina. The baseline (dash line) corresponds to an undisturbed vegetation area (non grazed).

intensity on plant floristic composition. Thus, long-term grazing at heavy stocking rates has tended to decrease plant species diversity and plant cover, and consequently by increasing bare areas. However, the biggest impact on grassland C ecosystem due to overgrazing was the C lost from soil (mainly the organic layer) as a consequence of soil erosion by strong winds.

3. Conclusions

Carbon storage has become an important issue in international negotiations on the management of greenhouse gas emissions, because increased carbon storage can be useful in offsetting emissions of carbon from fossil fuel burning and other sources. Estimates of native forest C storage under different management practices are required for estimating regional and national greenhouse gas balance. The use of functions provide a valuable tool for understanding and estimating C accumulation of primary forests of *N. antarctica* using forest inventories data. Also, we improved the understanding about the potential of C sequestration of *N. antarctica* forests under silvopastoral management. Thinning in silvopastoral systems may change the distribution of C allocation within a stand, due to reduction in the number of trees and return of C from litter. Stem-only harvesting rather than whole-tree removal, together with debarking the stem in situ, may reduce the loss of

soil C pool from the forest ecosystem. Furthermore, root systems from removed trees remain in the system, and could provide C to soil through decomposition. Therefore, for any particular forest management system it is important to analyse the development of both above- and belowground C over the forest life cycle for different site qualities for accurate quantification of C pools on regional scale.

C accumulation in grasslands and shrublands was strongly affected by plants composition, size and cover. In both ecosystems, it was critically important to quantify and understand belowground C allocation as well as soil C pools. Thus, quantification of roots C was important to improving our understanding of C cycles and storage in these ecosystems. In particular, long-term grazing intensity in grasslands was the main management practices that affected ecosystem C levels where overgrazing determined C lost mainly from soil as a consequence of soil erosion. Changes in grassland management that reverse the process of declining productivity can potentially lead to increased soil C. Therefore, proper grassland management is important to carbon sequestration.

4. Acknowledgment

I want to thank to Romina Lasagno, Verónica Gargaglione, Martín Viola and Juan Ruiz for their invaluable help during sampling in the field and contribution with data analysis.

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