DINÁMICA DEL CARBONO Y OTRAS INTERACCIONES EN UN SISTEMA SILVOPASTORAL EN FAJAS, UNA PLANTACIÓN DE PINO PONDEROSA Y UN PASTIZAL EN LA REGIÓN DE AYSÉN, PATAGONIA CHILENA

Dube, Francis[1]; Espinosa, Miguel[2]; Thevathasan, Naresh[3]; Gordon, Andrew[4]; Zagal, Erick[5]; Stolpe, Neal[6]

RESUMEN

Según las Naciones Unidas, el uso de sistemas agroforestales en terrenos degradados podría capturar entre 820 y 2.200 x 10^6 ton C $año^{-1}$ en un periodo de 50 años. El objetivo de este estudio es investigar el potencial de secuestro de carbono en un sistema silvopastoral con *Pinus ponderosa* y una plantación y pastizal en la Patagonia.

Se inventarió la biomasa arbórea y de pasto y se determinaron sus contenidos de C por combustión seca. Se recogió la caída de acículas una vez al mes, y se midió la descomposición de acículas, raíces de pasto y fecas de ganado mediante la técnica de bolsas de litera. Se determinaron los contenidos de C en lixiviados de suelo y emisiones de CO_2 por respiración de suelo.

Los resultados muestran que las tasas de descomposición están relacionadas con la temperatura de suelo y su contenido de humedad. La respiración de suelo es siempre mayor en la pradera y menor en la plantación. Los contenidos de C en la biomasa de pasto y árboles en el sistema silvopastoral superan los de la pradera y la plantación, respectivamente. La determinación de C orgánico de suelo a una profundidad de 0-40 cm demuestra que en el sistema silvopastoral el contenido de C es mayor, y que hay más C secuestrado en el suelo que en la biomasa vegetal correspondiente.

El sistema silvopastoral se ve como una alternativa muy interesante de captura de C, control de erosión y crecimiento de plantas.

Palabras claves: Captura de C, Andisol, caída de litera, descomposición, lixiviados, respiración de suelo.

1 Departamento de Silvicultura, Facultad de Ciencias Forestales, Universidad de Concepción, Victoria 631, Casilla 160C, Chile. Tel: (+56) 41 2204848 E-mail: fdube@udec.cl
2 Departamento de Silvicultura, Facultad de Ciencias Forestales, Universidad de Concepción, Victoria 631, Casilla 160C, Chile. Tel: (+56) 41 2204848 E-mail: mespinos@udec.cl
3 Department of Environmental Biology, Ontario Agricultural College, University of Guelph, Guelph, Ontario, N1G 2W1, Canada. Tel: (+1) 519 8244120 E-mail: nthevath@uoguelph.ca
4 Department of Environmental Biology, Ontario Agricultural College, University of Guelph, Guelph, Ontario, N1G 2W1, Canada. Tel: (+1) 519 8244120 E-mail: agordon@uoguelph.ca
5 Departamento de Suelos, Facultad de Agronomía, Universidad de Concepción, Vicente Méndez 595, Casilla 537, Chillan, Chile. Tel: (+56) 42 208853 E-mail: ezagal@udec.cl
6 Departamento de Suelos, Facultad de Agronomía, Universidad de Concepción, Vicente Méndez 595, Casilla 537, Chillan, Chile. Tel: (+56) 42 208853 E-mail: nstolpe@udec.cl

CARBON DYNAMICS AND OTHER INTERACTIONS IN A SILVOPASTORAL SYSTEMS ARRANGED IN STRIPS, A PONDEROSA PINE PLANTATION AND A NATURAL PASTURE IN THE AYSÉN REGION, CHILEAN PATAGONIA

ABSTRACT

According to the UN, the use of agroforestry systems on degraded lands could capture 820-2,200 x 10^6 t C $year^{-1}$ over a 50-year period. The objective of this study is to investigate the potential to sequester C in a *Pinus ponderosa*-based silvopastoral system arranged in strips, a plantation and natural prairie in Patagonia.

Tree and pasture biomass were inventoried and C contents determined by dried combustion. Needle fall was recollected once a month, and decomposition of needle, grass roots and cattle feces measured using the litterbag technique. Carbon in soil leachates and respired CO_2 were also determined.

The results show that decomposition rates were related to soil temperature and moisture contents. Soil respiration was highest in the prairie and lowest in the plantation. The C contents in grass and tree biomass in the silvopastoral system exceeded that of the pasture and the plantation, respectively. Determination of SOC at 0-40 cm depth shows that the silvopastoral system had the highest C contents, and there was more C in soil than corresponding plant biomass. The silvopastoral system appears as an interesting alternative for C sequestration, erosion control and plant growth.

Keywords: Carbon sequestration, Andisol, litterfall, decomposition, leachates, soil respiration.

INTRODUCTION

Recent studies performed in temperate regions worldwide have shown that agroforestry systems have greater C sequestration potential than monocropping systems, prairies, or forest plantations. Still, several of these studies have been performed under similar conditions and few have measured *in situ* C losses due to litter and crop decomposition, soil respiration, and soil lixiviation, which are all important when modeling C balance at the system level.

The study performed by Peichl *et al*. (2006) seems to be the only study known until now that compares the C fluxes and pools in agricultural and intercropping systems.

In Patagonia, ranchers increasingly face more problems to maintain cattle-raising productivity, a traditional activity that is often the only source of income. However, there is a limited scientific research on Chilean agroforestry systems that could be used to model C balances located in the temperate areas of the Southern Hemisphere, and especially those established on degraded volcanic soils.

Therefore, this study is likely to be the first to evaluate and model C sequestration potentials in *Pinus ponderosa* – based silvopastoral systems, plantations and pasture on degraded volcanic soils of the Chilean Patagonia.

MATERIAL AND METHODS

Site Description

The site was located in the San Gabriel Agroforestry Unit established in 2002 by INFOR, on a western exposed slope with 730 m altitude at 45°25’ SL and 72°00’ WL. Within the module, there are several land-use practices:

1) Natural pasture with traditional cattle grazing (PST),
2) 18-year-old *Pinus ponderosa* plantations (PPP),
3) Silvopastoral systems arranged in strips (SPS).

The annual precipitation ranges from 1000-1500 mm. However, only 15% of the precipitations occur between December and February, coinciding with the windiest period.

Mean temperatures fluctuate between 12 °C and 14 °C in summer and 2 °C and 3 °C in winter (Silva *et al*., 1999).

During summer, strong west winds are registered, provoking seasonal water deficit and the loss of soil organic matter due to wind erosion.

Tree and Pasture Biomass and C Content

Destructive sampling was performed to determine the weight of different tree components (trunks, branches, twigs, needles, cones and roots). To determine the fine root biomass, its annual production was estimated as a percentage of the litterfall. To obtain the total standing pasture biomass, the grass was manually harvested from 0.25 m^2 quadrants. To measure the subterranean biomass, the greatest quantity of roots growing were extracted and washed to remove soil particles and weighed (Gordon and Thevathasan, 2005). Carbon contents were obtained with a Fisons EA1108 CHNS-O Elemental Analyzer.

Recollection of Litterfall and Decomposition

The litter trap technique was used to collect needles that fall on the ground and determine their distribution (Berg and Laskowski, 2006). The amount of litterfall was sampled monthly for a 2-year period, and weekly during the rainiest months. The C contents were determined following the method describe above.

The litterbag technique was used to measure decomposition of organic material in contact with the soil. The bags with needles and feces were fixed on the F horizon, while the bags with root biomass were buried at 15 cm depth. The pine needles were sampled every six months for two years. The sampling of the grass roots and cattle feces was performed every three months for one year.

Soil C, Respiration and C Contents in Leachates

Soil samples were taken at 0-5; 5-20 y 20-40 cm depths in order to determine total, organic, and inorganic C content. C contents were determined using the combustion method as described above. Total soil respiration in closed chambers was measured monthly and weekly in summer (Edwards, 1982).

The C concentrations in leachates were measured on a monthly basis and weekly in the rainiest months using lysimeters at 80 cm depth. Total soluble organic C was analyzed using a TOC-V CPN Analyzer.

The soil moisture (20 cm depth), soil surface temperature (5 cm depth) and air temperature (+5 cm) were measured every two hours over a 24-month period using Decagon Devices EM-5B Data Loggers.

Statistical Analyses

All treatments were analyzed with the General Lineal Model procedure of SAS v.9.0 (SAS Institute, Carey, NC) for completely randomized designs. Analysis of variance was conducted using the ANOVA procedure with Tukey's HSD and Student's *t*-test, where applicable.

RESULTS

The C content was higher in every component of SPS as compared with PPP, but significant differences were found only for Twigs, Needles and Cones, Total aboveground, and Total tree (Table 1).

C contents decreased in the order Roots > Trunks > Branches > Twigs > Needles > Cones. For PPP and SPS, respectively, 64 and 69 % of total tree C were stored as aboveground biomass, whereas 36 and 31 % were stored within roots. Pine roots stored 11 % more C than the stem in PPP and only 2 % more C in SPS.

On a hectare basis, there was no significant difference between both treatments with respect to the amount of C stored in branches, twigs, needles and cones, besides the two-fold tree density in PPP.

Table 1
CARBON CONTENT OF DISTINCT TREE COMPONENTS FROM A PINE-BASED SILVOPASTORAL SYSTEM ARRANGED IN STRIP (SPS) AND A PLANTATION (PPP) IN THE CHILEAN PATAGONIA (AVERAGE ± STANDARD DEVIATION)

Tree components	(kg tree-1)		(kg ha-1)	
	PPP	SPS	PPP	SPS
Trunk	19.2 ± 4.8 a	23.0 ± 4.9 a	15350 ± 3829 a	9216 ± 1947 b
Branches	9.1 ± 5.9 a	12.6 ± 3.4 a	7291 ± 4755 a	5054 ± 1379 a
Twigs	2.3 ± 1.2 a	3.7 ± 1.1 b	1832 ± 952 a	1478 ± 436 a
Needles	7.6 ± 1.6 a	13.4 ± 4.1 b	6066 ± 1288 a	5341 ± 1636 a
Cones	0.2 ± 0.1 a	0.4 ± 0.04 b	144 ± 80 a	157 ± 15 a
Roots	21.3 ± 2.4 a	23.4 ± 4.8 a	17057 ± 1922 a	9372 ± 1912 b
Total aboveground	38.4 ± 13.2 a	53.1 ± 12.7 b	30683 ± 10577 a	21247 ± 5086 b
Total belowground	21.3 ± 2.4 a	23.4 ± 4.8 a	17057 ± 1922 a	9372 ± 1912 b
TOTAL	59.7 ± 15.5 a	76.5 ± 17.3 b	47740 ± 12379 a	30619 ± 6902 b

Values with the same lower case letter within a tree component and between treatments (PPP and SPS) for every group (kg tree-1 or kg ha-1) are not significantly different (Student's t test, **P<0.01).

Mean annual aboveground net primary productivity (ANPP) was similar in PST and SPS, but significantly larger than that of PPP. On a quadrant basis, ANPP was 20 % higher in SPS as compared with PST. In addition, mean soil moisture in the pasture portion of SPS was twice as much as PST during both growing seasons.

Litterfall in 2008-2009 was substantially lower than during 2007-2008 (Table 2). When comparing PPP and SPS, a significant difference was found only for needle fall in the second measurement period, being 1.6 times higher in PPP. With respect to litterfall distribution within SPS, approximately 54 % of the total fell within the tree strip, 40 % within 3 m east of the strip and 6 % within 3 m west. Said in other words, litterfall in the tree strip and within 3 m east from it accounted for 94 % of total litterfall biomass.

Table 2
LITTERFALL OVER A TWO-YEAR SAMPLING PERIOD IN A PINE-BASED SILVOPASTORAL SYSTEM ARRANGED IN STRIP (SPS) AND A PLANTATION (PPP) (AVERAGE ± STANDARD DEVIATION)

		Average		Distances in SPS		
Period	**Litterfall**	**PPP**	**SPS**	**in strip**	**3m west**	**3m east**
		(kg ha^{-1} y^{-1})		**(kg ha^{-1} y^{-1})**		
2007-	Needles	2116 ± 1,290 a	1,672 ± 1,310 a	2,080 ± 1,653 a A	235 ± 199 b B	1,574 ± 1179 a A
2009	Cones	373 ± 195 a	228 ± 56 a	284 ± 56 a A	10 ± 15 b B	224 ± 91 a A
	Total	2,489	1,900	2,364 A	246 B	1,797 A

Values with the same lower case letter within a litterfall type and between treatments (average) are not significantly different (Student's t test, *P<0.05). Values with the same lower case letter within a litterfall type and between PPP and one single distance in SPS (in strip, 3m west or 3m east) are not significantly different (Student's t test, *P<0.05). Values with the same higher case letter within a litterfall type and between distances in SPS are not significantly different (Tukey's HSD test, *P<0.05).

Carbon concentrations were significantly different at 0-5, 5-20 and 20-40 cm depths in all treatments, except at 5-20 and 20-40 cm depths in PPP (Table 3).

Among treatments, C % was similar at 0-5 cm depth in PST and SPS, but almost twice as high as PPP. At 0-40 cm depth, the C concentration also decreased in the order SPS > PST > PPP.

The C concentration reached a peak at 2.5 m on either sides of the strip, being higher eastward.

Among treatments, SOC was similar in the upper 5 cm in PST and SPS, but almost double and significantly different than in PPP.

At 0-40 cm depth, SOC also decreased in the order SPS > PST > PPP, showing that land-uses affected substantially SOC stocks.

There was a 30 % increase in SOC that resulted from the conversion of PPP to SPS but a 16% decrease from PST to PPP.

Table 3
SOIL ORGANIC C (%) AND CONTENTS (Mg ha-1) AT DISTINCT DEPTHS IN A NATURAL PASTURE (PST), A PINE PLANTATION (PPP) AND A SILVOPASTORAL SYSTEM ARRANGED IN STRIP (SPS) (AVERAGE ± STANDARD DEVIATION)

Treatment	Soil depth	SOC	SOC
	(cm)	(%)	(Mg ha-1)
PST	0-5	10.77 ± 0.74 A a	48.49 ± 3.34 A a
	5-20	5.62 ± 0.08 A b	75.85 ± 1.06 A b
	20-40	2.92 ± 0.50 A c	52.57 ± 9.08 A a
	0-40	4.92 ± 0.28 A	177.10 ± 10.09 A
PPP	0-5	6.25 ± 0.08 B a	28.12 ± 0.37 B a
	5-20	3.89 ± 0.05 B b	52.49 ± 0.70 B b
	20-40	3.81 ± 0.43 A b	68.65 ± 7.70 A c
	0-40	4.15 ± 0.20 B	149.25 ± 7.34 B
SPS	0-5	10.68 ± 0.35 A a	48.04 ± 1.57 A a
	5-20	6.51 ± 0.15 C b	87.94 ± 1.98 C b
	20-40	3.20 ± 0.21 A c	57.54 ± 3.73 A c
	0-40	5.38 ± 0.13 A	193.76 ± 4.61 A

Values with the same higher case letter within a column and within a same depth among treatments are not significantly different (Student's t test, $^{**}P<0.01$). Values with the same lower case letter within a column and within a same treatment are not significantly different (Tukey's HSD test, $^{*}P<0.05$).

Compared to PPP, soil respiration was similar within the tree strip and at 1 m from the strip in SPS, whereas at 7.5 m it was similar to PST (Table 4).

Among agroecosystems, total annual soil respiration was significantly higher in PST and lower in PPP.

At distinct locations within SPS, total soil respiration was not significantly different in the tree strip and at 1 from it, but significantly higher at a distance of 7.5 m.

Leached C concentration was highest in PPP, and it was slightly higher in PST than SPS.

Within SPS, C% was slightly higher in the tree strip than at 1 m from the trees, and the highest at 10.5 m from the strip, which also turned to be the middle of the pasture alley, although none of the differences were significant.

Table 4
TOTAL SOIL RESPIRATION (t CO_2 ha-1 y-1) AND C (%) OF LEACHED SOIL SOLUTION OVER TWO FIELD SEASONS, BETWEEN NOVEMBER 2007 AND 2009 (AVERAGE ± STANDARD DEVIATION)

Treatment	Soil respiration	C in leachates
	(t CO_2 ha-1 y-1)	(%)
PST	18.75 ± 0.29 A	0.0049 ± 0.0020 AB
PPP	15.63 ± 0.39 B	0.0056 ± 0.0024 A
SPS (mean)	16.94 ± 0.58 C	0.0044 ± 0.0008 B
SPS (in strip)	15.27 ± 0.53 a	0.0044 ± 0.0011 a
SPS (1m from strip)	15.98 ± 0.53 a	0.0040 ± 0.0011 a
SPS (7.5m from strip)	18.84 ± 0.68 b	n/a
SPS (10.5m from strip)	n/a	0.0048 ± 0.0016 a

Values with the same higher case letter within a column and among treatments (PST, PPP and SPS) are not significantly different (Student's t test, $^{**}P<0.01$). Values with the same lower case letter within a column and between locations in SPS (in strip, 1, and 7.5 or 10.5m from strip) are not significantly different (Tukey's HSD test, $^{*}P<0.05$).

DISCUSSION

Based on the results, it is clear that trees in SPS are using more efficiently the site resources (water, nutrients, light, etc.) and have their growth enhanced by the additional soil N provided by the leguminous pasture, resulting in larger amounts of C being sequestered.

In SPS, there is a favorable microclimate within and out of tree strips, and a synergy resulting from the positive interaction of active aerial and subterranean C cycles of the tree and grass components.

Sharrow and Ismail (2004), reported a more efficient C accretion in Douglas fir-subclover silvopastoral systems thanks to more active nutrient cycling patterns resulting from the association of forest and grasses in the same unit of land.

The significantly larger amounts of C stored in roots and trunks of PPP on an area basis were to be expected given the large difference of densities (Table 1). However, bigger trees in SPS compensate to a certain extent for the lower density, without forgetting the additional C sequestered in grass roots and soil pools, thereby making the silvopastoral system the best alternative of all.

The greater tree density in PPP and associated shade can explain why the mean annual ANPP therein was lower. The significantly larger soil moisture throughout the year at 2 m from the tree strip in SPS and the higher air temperature during the growing seasons may help to understand why ANPP was higher in SPS than PST on a quadrant basis. In addition, mean soil moisture in the pasture portion of SPS was twice as much as PST during both growing seasons.

The lower litterfall in 2008-2009 was to be expected since trees were pruned to a 4-m height at the beginning of 2008, without forgetting the effects of the drought in the previous year. Although trees were bigger in SPS and contained 70 % more needle biomass, the half tree density impacted severely litterfall, at least in the first years after pruning. The predominant winds blowing eastward across the year were largely responsible for the low litterfall input within 3 m west. Within SPS, litterfall was slightly higher in the tree strip than within 3 m east of it, but no significant difference was observed. However, litterfall within 3 m west was significantly lower than at any other locations, except in the 2007-2008 period where needlefall was similar on either sides of the strip. One possible explanation for this similarity could be the lack of strong winds during the main period of needle shedding from the trees, allowing a “more homogeneous” distribution of litterfall across SPS.

The data suggest that the plantation transition into silvopastoral system resulted in more C being sequestered at 0-20 and 0-40 cm depths in SPS, while there was a significant loss of soil C at the same depths after the establishment of the Pine plantation on the natural prairie. Other studies have shown increases of soil C following conversion of plantations to intercropping systems (Bambrick *et al*., 2010) and decreases after afforestation of pastures with first-rotation pine plantations (Dube *et al*., 2009).

On the other hand, the larger C concentrations observed from the distance of 2.5 m until the middle of the alley in SPS could be attributed to the better growth and yield of pasture in contrast with PST, resulting in more N being fixed by clover and stored in soil at 0-20 cm depth and therefore, more C being accreted. In addition, the remaining pine stumps and coarse roots left in the alleys after converting the plantation to SPS, as well as the regular inputs of lignin-rich litter from the trees represent an important source of chemically recalcitrant C that may contribute to significant gains in SOC (Montagnini and Nair, 2004).

For every agroecosystem and distinct locations within SPS, there was a significant negative correlation (Pearson’s coefficient) between respiration and soil moisture, and highly significant positive correlations between soil respiration and superficial air temperature and soil temperature. This is in agreement with the findings of Lee and Jose (2003) for temperature, where the lowest fits were also encountered in the monocultures, but in disagreement with soil moisture, although the fits were rather low as compared with soil temperature. The regular litterfall and shade provided by the tree cover in SPS strip and PPP resulted in lower mean annual air and soil temperature, contributing to decrease total soil respiration.

The high C concentration at 10.5 m from the tree strip within SPS could be attributed to the presence of decomposing stumps and structural/coarse roots since the conversion of the plantation into SPS. Additionally, trees in PPP produce detritus such as needles, twigs, branches (including those from pruning), root exudates, and dead roots, which represent another source of organic C than can be dissolved in the soil solution (Kimmins, 2004). This could also explain why leached C is higher in PPP, taking also in consideration the half tree density in SPS, and why dissolved C follows the same pattern within and at 1 m from the tree strip in SPS.

CONCLUSIONS

Depending on their management, land-uses may become a source or sink of CO_2 and can impact on net CH_4 and N_2O emissions to the atmosphere.

Several recent studies performed in temperate regions around the world have shown that agroforestry as an integrated land-use has greater C sequestration potential than monocropping systems, prairies, or even forest plantations.

Sound management can make agroforestry systems effective CO_2 sinks, especially with the use of perennial crops and fast growing tree species that increase soil sinks in the short term.

In isolated regions such as Patagonia, the adoption of silvopastoral systems appear to be a sustainable practice that satisfies socio-economic needs of rural population, optimize land productivity, control erosion processes, preserve C and N pools during decades or centuries, and contribute to reduce atmospheric CO_2.

ACKOWLEDGEMENTS

We sincerely wish to acnowledge and express our sincere thanks to Mr. Victor Mata for hosting the research sites in his property near Coyhaique, to Silvia Marchetti and Luis Alvarez for assistance in the field, to Forestal Mininco S.A. - Aysén Project for logistics and laboratory analysis. Special thanks are also given to Centro Trapananda (University Austral of Chile), and Center for Investigations of Ecosystems in the Patagonia (CIEP) for logistics and support. In addition, we sincerely thank INFOR for sharing valuable information and data and authorizing the establishment of the plots in the San Gabriel Agroforestry Unit. This study was funded by a grant (Project No. 207.142.025-1.0) from the Direction of Investigations (DIUC) of the University of Concepción. Additional financial support was also obtained from CONICYT of the Chilean Government through a doctoral scolarship and from QMI-SAI Global Canada Inc.

REFERENCES

Bambrick, A. D., Whalen, J. K., Bradley, R. L., Cogliastro, A., Gordon, A. M., Olivier A., Thevathasan, N. V., 2010. Spatial heterogeneity of soil organic carbon in tree-based intercropping systems in Quebec and Ontario, Canada. Agroforest. Syst. 79: 343-353.

Berg, B. and Laskowski, R., 2006. Litter decomposition: A guide to carbon and nutrients turnover. Adv. Ecol. Res., vol. 38, Elsevier Acad. Press, San Diego, USA, 428 pp.

Dube, F., Zagal, E., Stolpe, N., Espinosa, M., 2009. The influence of land use change on the organic carbon distribution and microbial respiration in a volcanic soil of the Chilean Patagonia. Forest Ecol. Manage. 257: 1695-1704.

Edwards, N. T., 1982. The use of soda-lime for measuring respiration rates in terrestrial systems. Pedobiologia 23: 321-330.

Espinosa, M., Acuna, E., Cancino, J., Munoz, F., Perry, D. A., 2005. Carbon sink potencial of radiata pine plantations in Chile. Forestry 78(1): 11-19.

Gordon, A. M. and Thevathasan, N. V., 2005. How much carbon can be stored in Canadian agroecosystems using a silvopastoral approach? In: Silvopastoralism and sustainable land management. Mosquera-Losada M.R., Rigueiro-Rodriguez, A. McAdam J. (eds) CABI Publishing, Wallingford, UK, pp. 210-218.

Kimmins, J. P., 2004. Forest ecology: a foundation for sustainable forest management and environmental ethics in forestry. 3rd Ed. Prentice Hall, Upper Saddle River USA 611 pp.

Lee, K. H. and Jose, S., 2003. Soil respiration and microbial biomass in a pecan - cotton alley cropping system in Southern USA. Agroforest. Syst. 58: 45–54.

Montagnini, F. and Nair, P.K.R., 2004. Carbon sequestration: an underexploited environmental benefit of agroforestry systems. Agroforest. Syst. 61: 281-295.

Peichl, M., Thevathasan, N. V., Gordon, A. M., Huss, J. and Abohassan, R., 2006. Carbon sequestration potentials in temperate tree-based intercropping systems, southern Ontario, Canada. Agroforest. Syst. 66: 243-257.

Sharrow, S. H. and Ismail, S., 2004. Carbon and nitrogen storage in agroforests, tree plantations, and pastures in western Oregon, USA. Agroforest. Syst. 60: 123-130.

Silva, F., Ahumada, F. y Cerda, J., 1999. Guías de condición para pastizales de la Ecorregión Templada Intermedia de Aysén. Departamento de protección de recursos naturales renovables, SAG, Gobierno Regional de Aysén, Chile. 127 pp. (in Spanish).