International Grassland Congress Proceedings
22nd International Grassland Congress

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This document is available at https://uknowledge.uky.edu/igc/22/1-16/3

The 22nd International Grassland Congress (Revitalising Grasslands to Sustain Our Communities) took place in Sydney, Australia from September 15 through September 19, 2013.

Proceedings Editors: David L. Michalk, Geoffrey D. Millar, Warwick B. Badgery, and Kim M. Broadfoot

Publisher: New South Wales Department of Primary Industry, Kite St., Orange New South Wales, Australia

Presenter Information

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Productivity and carbon storage in silvopastoral systems with *Pinus ponderosa* and *Trifolium* spp. plantations and pasture on a volcanic soil in the Chilean Patagonia

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Abstract. Little information is available about carbon (C) sequestration potentials in ecosystems on Andisols of the Chilean Patagonia. This study was undertaken to measure the size of the C stocks in three predominant ecosystems: *Pinus ponderosa*-based silvopastoral systems (SPS), pine plantations (PPP) and natural pasture (PST), and to examine how clover (*Trifolium* spp.) affect tree growth and stocks of soil C. The C contents of trees and pasture were determined by destructive sampling and dry combustion. Soil samples were taken at 0-5, 5-20, 20-40 cm depths in order to determine soil C and N. For PPP and SPS, respectively, 38.4 and 53.1 kg/tree of total tree C were stored aboveground, whereas 21.3 and 23.4 kg/tree were stored belowground. Tree diameter at breast height increased 1 and 2 cm/year in PPP and SPS, respectively, and was significantly higher in SPS, an interesting value for the region. Tree growth in SPS was enhanced by lower tree competition and the additional soil N provided by the leguminous pasture, resulting in larger amounts of C being sequestered. Soil organic C (SOC) stocks at 0-40 cm depth were 193.76, 177.10 and 149.25 Mg/ha in SPS, PST and PPP, respectively. The conversion of PPP to SPS and PST to PPP resulted in an increase of 44.51 Mg/ha and a decrease of 27.85 Mg/ha in SOC, respectively, at 0-40 cm soil depth. A favourable microclimate (air temperature, soil moisture) has been observed in SPS as well as a synergistic effect between trees and pasture.

Keywords: Andisols, C stocks, N storage, growth, ponderosa pine, silvopasture.

Introduction

Between 1850 and 2000, atmospheric concentrations of carbon dioxide (CO_2) rose from 280 to 369 ppm, and increased further to 388 ppm by August 2010, a 5.1% rise over the last 10 years (Tans 2010). The Climate Change 2007 Synthesis Report (IPCC 2007) proposed several management strategies in the agricultural sector to mitigate CO_2 concentrations in the atmosphere. Agroforestry systems rate high in this regard, because with appropriate management, and the use of perennial pastures and fast growing trees, they increase soil C sequestration in the short term and therefore are effective CO_2 sinks.

In the remote region of the Chilean Patagonia, ranchers are increasingly challenged to maintain pasture and livestock productivity because of the windy inhospitable climate, steep topography, and eroded volcanic soils. Consequently, the Forestry Research Institute has recently implemented various incentives for landowners to adopt sustainable agroforestry on their properties, mostly silvopastoral systems and windbreaks, in order to improve the overall productivity of the land, control erosion processes, and increase C sequestration capacity.

Nevertheless, there is a general lack of scientific research on C stocks in silvopastoral systems located in the temperate areas of the Southern Hemisphere, and especially those established on degraded volcanic soils. The current study is the first to evaluate C sequestration potentials (aboveground and in soil) in ecosystems on degraded Andisols of the Chilean Patagonia. The objectives of this work were to: (1) measure the size of the C stocks that are present in the vegetation biomass and volcanic soils in a natural pasture, a managed *P. ponderosa* plantation, and a pine-based silvopastoral system; and (2) examine how leguminous pasture (*Trifolium* spp.) affect tree growth and the concentration and stocks of soil C.

Methods

The study took place in the Intermediate Agro-ecological Zone of the Aysén Region of Patagonia, one of the most climatically extreme and southern zones of the Chilean territory. The site was established in 2002 jointly by the Agricultural and Cattle Development Institute (INDAP) and Forestry Research Institute (INFOR) 30 km north of the city of Coyhaique, on a westerly exposed slope at 730 m altitude, Lat S 45°25’ and Long W 72°00’. The annual precipitation ranges between 1000 mm and 1500 mm. Mean temperatures fluctuate between 12°C and 14°C in summer and 2°C and 3°C in winter. The soil was classified as medial, amorphic, mesic Typic Hapludands (Stolpe *et al.* 2010). The study area included several adjacent land-management practices (200 m apart), hereafter referred to as treatments: (1) natural pasture with traditional cattle grazing (PST); (2) an 18-year-old plantations of thinned and pruned *P. ponderosa* (PPP); (3) silvopastoral systems of *P. ponderosa*-arranged in strips (SPS), with pasture alleys of 21 m width between the tree strips (6 m wide). In 1991, *P. ponderosa* plantations were established over the pasture, with a density of 2000 trees/ha and a spacing of 2 m x 2.5 m. In 2003, part of the plantation (5 ha) was thinned down to 800 trees/ha while another 5 ha was thinned to 400 trees/ha and converted into a silvopastoral system arranged in strips (Dube *et al.* 2011). The pasture in PST and SPS and consisted of a mixture of perennial pastures (*Dactylis glomerata*, *Holcus lanatus*, *Poa pratensis*), legumes (*Trifolium pratense*, *T. repens*), and other accompanying species. Both treatments were grazed with a stocking density of 0.5 cows/ha.

Treatments were established in October 2007 in a completely randomized design with three replicates. The plots had a uniform westerly exposure and a slope of 10-15%. In SPS, each plot included three strip rows of pines (6 m wide) and half strip (10.5 m in length along the tree rows) of pasture on either side. In both PPP and PST, the plots had only pine and pasture, respectively. All plots were fenced with barbed wire and chicken wire to exclude animals.

An inventory of PPP and SPS was performed in 2007, 2008 and 2009 to determine DBH (diameter at breast height) and HT (height). Destructive sampling was performed to determine the weight of different tree components. Once the trees were felled, the fresh biomass of trunks, branches, twigs, needles and cones were measured using a 45-kg dynamometer. Three sub-samples from each tree component were then taken in order to determine the moisture and C concentrations. Total C of every component was determined using a Fisons EA1108 CHNS-O Elemental Analyser (Fisons Instrument, CA, USA).

In order to determine the annual above- and below ground net primary productivity of pasture grasses, and simulate animal grazing, the forage material was harvested three times during each growing season over a two-year period. Vegetation was cut within 0.5 m^2 quadrats that were permanently established in the plots of every treatment, and located at a minimum of 3 m from the edge of the plot to prevent the border effect.

Soil samples were taken at 0-5, 5-20, 20-40 cm depths to determine C and N stocks in each treatment. In each SPS plot, the samples were taken following two transects perpendicular to the pine strip, one in each direction at 2.5 m intervals from the edge of the tree strip, up to 10 m on either side. In PPP and PST, samples were randomly collected at the same depths in each plot. The total organic C and total N were determined using the Elemental Analyser following the dynamic flash combustion technique at 1800°C.

The soil moisture (0-20 cm depth) and ambient air temperature (+5 cm) were measured every two hours over a 24-month period using EC-20 soil moisture sensors and ECT temperature sensors, respectively, that were connected to EM-5B Data Loggers (Decagon Devices Inc., Pullman, WA, USA). Within PPP and PST, loggers were randomly installed in different locations in each plot, whereas in the SPS, a logger was placed in the middle of the tree strip and another one at 2 m from the strip, far from the border of the plot. All treatments were analysed with the General Lineal Model procedure of SAS v.9.0 (SAS Institute Inc. 2003) for completely randomized designs to test the effect of treatments.

Results

Carbon concentrations (%) and stocks (kg/tree and kg/ha) of the distinct compartments of above and belowground biomass from the pines in PPP and SPS are shown in Table 1. The C concentrations (%) of individual and total aboveground components were similar in both treatments, but there was a significant difference only in the pine needle component, with that being higher in SPS.

On a tree basis, the C stocks were higher in every component of SPS compared with PPP, but significant

Table 1. Carbon concentrations (%) and stocks (kg/tree and kg/ha) of different tree components from a *Pinus ponderosa* plantation (PPP) and a silvopastoral system (SPS) in Chilean Patagonia (mean ± standard deviation).

Tree components	C%		kg/tree of C		kg/ha of C	
	PPP	SPS	PPP	SPS	PPP	SPS
Trunk	51.4 ± 1.0 a D	51.7 ± 0.8 a C	19.2 ± 4.8 a	23.0 ± 4.9 a	15350 ± 3829 a	9216 ± 1947 b
Branches	52.8 ± 0.5 a CD	53.4 ± 1.0 a BC	9.1 ± 5.9 a	12.6 ± 3.4 a	7291 ± 4755 a	5054 ± 1379 a
Twigs	53.7 ± 0.8 a ABC	53.2 ± 1.2 a BC	2.3 ± 1.2 a	3.7 ± 1.1 b	1832 ± 952 a	1478 ± 436 a
Needles	55.2 ± 0.3 a AB	56.2 ± 0.7 b A	7.6 ± 1.6 a	13.4 ± 4.1 b	6066 ± 1288 a	5341 ± 1636 a
Cones	55.5 ± 1.0 a A	54.4 ± 0.1 a AB	0.2 ± 0.1 a	0.4 ± 0.04 b	144 ± 80 a	157 ± 15 a
Roots	53.2 ± 1.3 a BCD	52.5 ± 1.4 a BC	21.3 ± 2.4 a	23.4 ± 4.8 a	17057 ± 1922 a	9372 ± 1912 b
Total aboveground	53.7 ± 0.4 a ABC	53.8 ± 0.4 a B	38.4 ± 13.2 a	53.1 ± 12.7 b	30683 ± 10577 a	21247 ± 5086 b
Total belowground	53.2 ± 1.3 a BCD	52.5 ± 1.4 a BC	21.3 ± 2.4 a	23.4 ± 4.8 a	17057 ± 1922 a	9372 ± 1912 b
Total tree	53.6 ± 0.5 a	53.6 ± 0.4 a	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 or kg/ha) are not significantly different (Student's t test, **$P < 0.01$). Values with the same upper case letter within a column and among tree components (trunk, branches, twigs, needles, cones, roots) or among totals (total aboveground and belowground) are not significantly different (Tukey's HSD test, *$P < 0.05$).

Table 2. Above- and belowground net primary productivity (kg/ha/y) of pasture in a prairie (PST), a pine-based silvopastoral system (SPS), and a *Pinus ponderosa* plantation (PPP) over a two-year period. Measurements were taken in December 2007 and 2008, and February and May 2008 and 2009 (mean ± standard deviation).

	Aboveground dry biomass yield (ANPP) (kg/ha/y)			Belowground dry biomass yield (BNPP) (kg/ha/y)		
Year	PST	SPS	PPP	PST	SPS	PPP
2008	2954 ± 1027 a	2458 ± 828 a	n/a	6010 ± 392 a	4697 ± 291 b	n/a
2009	3391 ± 932 a	3368 ± 594 a	732 ± 18 b	6329 ± 422 a	5074 ± 334 b	1875 ± 112 c
Mean	3173 ± 309 a	2958 ± 580 a	732 ± 18 b	6170 ± 428 a	4885 ± 360 b	1875 ± 112 c

Values with the same lower case letter within a same year and among treatments are not significantly different (n/a: not applicable; Student's *t* test, **P* < 0.01).

differences were found only for twigs (61% higher), needles (76%) and cones (100%), total aboveground (38%) and total tree (28%). For PPP and SPS, respectively, 64% (38.4 kg C /tree) and 69% (53.1 kg C /tree) of total tree C were stored as aboveground biomass whereas 36% (21.3 kg C /tree) and 31% (23.4 kg C /tree) were stored within the root system. Additionally, 32 and 39% of total C in PPP and SPS, respectively, was stored in branches, twigs, cones and needles, which together represent a potential C input to the soil C stock via litterfall and branch pruning. When looking at the data on a hectare basis, there was significantly more C stored in roots (82% larger) and trunks (67%) in PPP. The difference between PPP and SPS was reduced to only 44% when comparing total aboveground C stocks, implying more efficient C storage per tree in SPS. Tree DBH increased 1 and 2 cm per year in PPP and SPS, respectively, and DBH was significantly higher each year in SPS than PPP (5, 6 and 8%, respectively, in 2007, 2008 and 2009).

Above- and belowground net primary productivity of pasture growing in the ecosystems are presented in Table 2. Both ANPP and BNPP were higher in 2009 than 2008. In addition, although the mean ANPP was slightly larger in PST than SPS, it was not significantly different. However, on a quadrat basis (g/0.5 m^2), ANPP in SPS was 11 and 28% higher than PST in 2008 and 2009, respectively (F. Dube, unpublished data 2010). Although the area available for pasture was 22% lower in SPS, the overall ANPP was only 14% lower in 2008 and almost the same in 2009.

Carbon concentrations were significantly different at 0-5, 5-20 and 20-40 cm depths within the three treatments. In PST and SPS, C concentration at 0-20 cm depth was more than double the concentration at 20-40 cm depth, while in PPP it was only 20% higher. Among treatments, the C concentration was similar at 0-5 cm depth in PST and SPS, but almost twice as high as PPP, that difference being significant.

Discussion

The presence of herbaceous legumes (*T. pratense* and *T. repens*) could perhaps explain why pine needles in SPS contained significantly more C than any other tree components (Table 1). Clover was seeded soon after the establishment of SPS 6 years ago, and likely influenced through symbiotic fixation the amounts of soil N at 0-40 cm depth that were measured in 2009, which were significantly higher than in PPP. Although it may take several years before tree growth can be enhanced by soil N enrichment, the results from this study indicated that SPS with leguminous pasture alleys had a greater increase of tree diameter compared to PPP. The significantly larger amounts of C stored in roots and trunks of PPP on an area basis (kg/ha) were expected considering the large difference of the tree densities. However, bigger trees in SPS compensate to a certain extent for the lower density, not including the additional C sequestered in pasture roots and soil stocks. Considering that individual trees in SPS sequestered 30% more C in the total above and belowground biomass compared to PPP suggests that a moderate increase in tree density with slight modification to the system design could further enhance C sequestration in the tree component.

The drought that occurred in summer of 2008 reduced pasture growth in both PST and SPS, as compared with productivity in 2009. However, the ANPP in SPS was only slightly lower than PST in 2008 and almost the same in 2009, which demonstrates the strong influence exerted by trees in the creation of a favourable microclimate within the pasture alleys of SPS. Trees in silvopastoral systems reduce wind speed and moisture loss via evapotranspiration, and cause an increase of air temperature, which help the growth of pasture. The thermal cover provided by trees may help to prevent frost damage to the pasture portion and increase the length of the growing season. The greater tree density in PPP and increased shading can explain why the mean annual ANPP was lower compared with PST and SPS. Throughout the year, at 2 m from the tree strips in SPS, the air temperature was higher (2.3°C in 2008 and 1.1°C in 2009) and the soil moisture was greater than PST, which helps to understand why ANPP was higher on a quadrat basis (g/0.5 m^2) in SPS than PST. In fact, the mean soil moisture in the pasture portion of SPS was twice as high as that of PST during both growing seasons. With respect to the higher annual BNPP encountered in PST as compared with SPS, this could be attributed to the harsher environment under which PST is growing, forcing the pasture to develop more extensive root systems where photosynthate reserves can be stored. Soil moisture over the two-year measurement period was substantially lower in PST than SPS, with a mean annual difference of 5%, whereas the annual air temperature in PST was almost 1.5°C less (Dube *et al.* 2011).

The larger concentrations of soil N in SPS are linked to greater C concentrations and gains in SOC storage, which may result in the amelioration of soil fertility. The data suggest that the plantation transition into SPS 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 establishing PPP on the natural pasture. The presence of legumes since the establishment of SPS resulted in significantly greater amounts of soil N stored at any location of SPS than within PPP, and it has been shown that soil C and N stocks can be increased by 20-100% with the presence of N-fixing plants (Johnson 1992).

Conclusion

Several recent studies performed in temperate regions of the world have shown that agroforestry as an integrated land-use system has greater C sequestration potential than monoculture cropping systems, or even forest plantations. In the Chilean Patagonia, the adoption of silvopastoral systems appear to be a sustainable practice that optimizes land productivity, preserves and increases C and N stocks during centuries, and also contributes to reduce atmospheric CO_2. The presence of herbaceous legumes since the establishment of SPS resulted in significantly greater amounts of soil N stored at any location of SPS compared with PPP, and the larger soil N concentrations are linked to greater C stocks and gains in SOC storage.

Acknowledgements

We sincerely wish to acknowledge and express our sincere thanks to Mr. Victor "Titi" Mata for hosting the research sites in his property near Coyhaique. This study was funded by a grant (Project No. 207.142.025-1.0) from the Direction of Investigations of the University of Concepción (DIUC). Additional financial support was also obtained from CONICYT of the Chilean Government.

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