DISTRIBUTION OF SOIL ORGANIC CARBON STOCK IN AN ALFISOL PROFILE IN MEDITERRANEAN CHILEAN ECOSYSTEMS

Cristina Muñoz[1], Carlos Ovalle[2] and Erick Zagal[1]

[1] Departamento de Suelos y Recursos Naturales, Facultad de Agronomía, Universidad de Concepción, P.O.Box 537, Av. Vicente Méndez 595, Chillán, Chile.
Corresponding author: ezagal@udec.cl.
[2] Instituto de Investigaciones Agropecuarias, CRI Quilamapu, P.O.Box 426,
Av. Vicente Méndez 515, Chillán, Chile.

Distribución del carbono orgánico del suelo almacenado en el perfil de un Alfisol en ecosistemas Mediterráneos de Chile

Key words: *Acacia caven*, degraded ecosystems, soil use intensity

ABSTRACT

The overexploitation of the natural resources in the Mediterranean-type climate region of Chile, has resulted in natural forest fragmentation and expansion of *Acacia caven* (Mol), forming the ‘Espinal’ ecosystem (EE) that includes two million of hectares in the Central part of Chile. The effect of the anthropogenic intervention over the soil organic carbon (SOC) in these ecosystems is unknown. The aim of this study was to quantify the SOC stocks and it profile distribution in the EE. This was achieved by collecting soils samples according to soil coverage percentage canopy from: well-preserved Espinal (WPE), 51-80 %; good-preserved (GE), 26-50 %; degraded (DE), 11-25 % and very degraded (VDE), 0-10 %. We also included a native forest (NF), 80-98 % of soil coverage to evaluate the pristine condition ecosystem. Soil samples were collected under canopy of *A. caven* and from intercanopy (1.5 m outside) at four depths (0-5, 5-10, 10-20 and 20-40 cm). SOC was determined by wet oxidation and colorimetric analysis. Native forest had 50 % more SOC content than EE. Soil coverage was directly related to SOC content, having WPE and GE 44 % more SOC stock than DE and VDE. *A. caven* canopy increased 25 % the C stock in the profile compared to intercanopy. In conclusion, the EE presented an elevated potential for increase SOC stock under canopy, and therefore this represents a potential carbon sink that contribute to atmospheric CO_2 reduction.

Palabras claves: *Acacia caven*, ecosistemas degradados, intensidad de uso del suelo

RESUMEN

La sobreexplotación de los recursos naturales en la zona Mediterránea de Chile, ocasionó la fragmentación del bosque nativo y la expansión de *Acacia caven* (Mol), formando los ecosistemas de Espinal (EE) que abarcan dos millones de hectáreas en la zona central de Chile. El efecto de esta intervención antropogénica sobre el carbono orgánico del suelo (SOC) en este ecosistema es desconocido. El objetivo de este estudio fue cuantificar el almacenamiento de SOC y su distribución en el perfil en los EE. El estudio fue realizado mediante la recolección de muestras de suelo desde Espinal bien preservado (WPE), 51-80 % cobertura de suelo; bueno (GE), 26-50% cobertura de suelo; degradado (DE), 11-25 % cobertura de suelo y muy degradado (VDE), 0-10 % cobertura de suelo. Además, se incluyó un bosque nativo (NF), 80-98 % cobertura de suelo, para evaluar la condición prístina de los ecosistemas. Las muestras de suelo fueron colectadas bajo la canopia de *A. caven* y desde intercanopia (1.5 m fuera), ambas a cuatro profundidades (0-5, 5-10, 10-20 y 20-40 cm). SOC fue determinado mediante oxidación húmeda y análisis colorimétrico. NF almacenó más de 50 % del contenido de SOC que EE. La cobertura del suelo estuvo directamente relacionada al contenido de SOC, teniendo WPE y GE 44 % más SOC que DE y VDE. La canopia de *A. caven* incrementó 25 % el almacenamiento de SOC en el perfil comparado a intercanopia. En conclusión, EE presentó un elevado potencial para incrementar el almacenamiento de SOC bajo su canopia, representando un potencial sumidero de C que contribuye a la reducción del CO_2 atmosférico.

INTRODUCTION

Mediterranean climate areas are important bio-geographic zones with great plant diversity, representing 20 % of the world's floristic diversity, including 5 % of the earth's surface, and distributed in five geographic areas such as Central-south of Chile, South Africa and South-east Australia (Cowling *et al.*, 1996, *Davis et al*, 1997).

Mediterranean- type climate region of Chile sustains 53 % of the total population of the continent (INE, 1995) and possesses 50 % of the vegetation species diversity (Arroyo and Cavieres, 1997). Over-grazing and over-exploitation of natural resources has depleted soil nutrients, reducing both, productivity and biodiversity; at the same time turning out native forest fragmentation (Echeverria *et al*, 2006) and biological invasion of *Acacia caven* (Mol) shrubs tree. *A. caven* is one of 900 *Acacia* species distributed in the world, which dominate arid and semi-arid climates and provide stability and productivity in agricultural and livestock production agro-ecosystems. *A. caven* is considered to be originally from the Chaco Region (Eastern side of the Andes Mountains) and was introduced in Chile prior to the Spanish Conquest (Aronson, 1992). *A. caven* is widely distributed in other areas such as Northern Argentina, Paraguay and Southern Bolivia (Ovalle *et al.*, 1990, 1996). This anthropogenic formation have had deeply impact on a complex vegetation structure referred to as ‘pseudo-savanna’, conformed by an herbaceous stratum mainly consisting in annual species and a woody stratum of *A. caven*, forming EE (*i.e.* the ‘Espinal’ ecosystems) (Ovalle *et al.*, 1990). The EE consist of an agricultural leaving system with different Espinal conservation and degradation levels, resulting in a heterogeneous landscape leaving variable space for different land uses (Ovalle *et al.*, 2006; Montenegro *et al.*, 2003). The Espinal ecosystem cover 2 millions hectares in Chile, from the non-irrigated area of the Central Valley until Eastern side of the Coastal Mountains. They are distributed in a wide variety of climatic conditions, ranging from an arid region with 160 to 200 mm mean annual precipitation (8-9 months drought) until the humid region with 1000-1200 mm mean annual precipitation (4-5 months drought). This area contains a large part of cattle and grain crops production (Ovalle *et al.*, 1999).

Soil organic carbon is a key component of EE such as in others ecosystems as well (Guo and Gifford, 2002). Muñoz *et al*. (2006) showed partial results of C stock and biological parameters of EE. The present research is a complementary study that will show the SOC stocks in the soil profile of different scenarios of EE in a coverage gradient.

MATERIALS AND METHODS

Study area and soil sampling

The study was carried out in the Province of Cauquenes, Seventh Region of Chile, in an area located in a sub-humid portion of the Mediterranean-type climate region of Chile (35º 58’ S, 72º 17’ O), under dry land conditions. A detailed description is in Muñoz *et al*, (2006). This zone presents an average mean annual precipitation of 695 mm with 5 months of summer drought and a global aridity index of 0.38 ly (1 ly = 1 cal/cm^2). The mean soil temperature at 10 cm depth is 21.3 ºC during January-February and 9.4 ºC in June-July, and 12.6-14ºC in November-December. The study area’s altitude is 170-180 masl (Santibáñez and Uribe, 1993). The cattle managements in this area is mainly ovine and bovine with about two ovine per hectare per year (Ovalle *et al.*, 1999). Table 1 summarize the sampling locations, which were classified according to the *A. caven* coverage percentage. Soils in this area are Alfisol classified as fine, mixed, active, mesic Ultic Palexeraf, formed *in situ* from granite rock with a smooth-clayey textural profile where kaolinite is the dominating clay minerals (CIREN, 1994, Stolpe, 2006).

Topography shows complex slopes that vary between 2 to 8 % and steep slope ranging from 9 to 20 %. Soil depth varies depending on the extent of soil erosion. Rooting depth is until 75-100 cm and porosity is from common to abundant. There is a great presence of quartz content in the pedon-profile and the permeability is moderate (CIREN, 1994, Stolpe, 2006).

In the study area, the herbaceous stratum is dominated by approximately 350 species of annual plants, presenting a great heterogeneity due to the landscape diversity and human action. The floristic composition of the herbaceous vegetation in these ecosystems is directly influenced by the presence of *A. caven*, including the species linked to the tree canopy: *Lolium multiflorum*, *Vulpia dertonensis*, *Avena barbata* and *Briza maxima* as well as the species linked to the outside tree: *Leontodon nudicalis*, *Briza minor*, *Medicago polymorpha* and *Hordeum berteroanum* (Ovalle *et al.*, 2006). Soil sampling was conducted in a gradient of vegetation coverage in five EE distributed in a longitudinal transect of 23,000 ha. The gradient was from well-preserved Espinal (WPE), 51-80 % soil coverage, good-preserved (GE), 26-50 % soil coverage, degraded (DE), 11-25 % soil coverage and very degraded (VDE), 0-10 % soil coverage. A native forest (NF), 80-98 % coverage was also included to evaluate the pristine ecosystem condition (Muñoz *et al.*, 2006). Four plots of 500 m^2 (25 x 20 m) for each EE were evaluated. At each site the vegetation tree (*A. caven* 30-60 years old with an average height of 2.7 m and an average crown diameter of 2.2 m) was marked and soil was sampled exactly under tree coverage; the distance of about half the tree canopy. The other sample (intercanopy) was taken about 1-1.5 m outside the canopy. The two samples were taken at 0-5, 5-10, 10-20 and 20-40 cm. depth. All soils were air-dried, sieved and stored at 4 °' al C until analysis.

Table 1: Classification of Espinal ecosystems according to *A. caven* coverage in the Mediterranean zone of Chile.
Cuadro 1: Clasificación de los ecosistemas de Espinal de acuerdo al porcentaje de cobertura de *A. caven* en la zona Mediterránea de Chile.

Ecosystem	Coverage (%)	Density (trees ha^{-1})	Coverage Weighting	
			Under canopy	Intercanopy
Native Forest (NF)	80-98	Not determined	0.98	0.02
Well preserved Espinal (WPE)	51-80	909 ± 154	0.80	0.20
Good Espinal (GE)	26-50	604 ± 201	0.50	0.50
Degraded Espinal (DE)	11-25	375 ± 130	0.25	0.75
Very degraded Espinal (VDE)	0-10	308 ± 51	0.10	0.90

SOC determination

The level of SOC in the soil was determined by wet oxidation and colorimetric analysis (Sims and Haby, 1971). Briefly, 0.5 g of air-dried soil was weighed in a 150 mL Erlenmayer flask, then 10 mL of a sodium dichromate solution 0.5 M and 20 mL of concentrate sulfuric acid (96 %) were added. The mixture was shaken and left to rest for 30 minutes. Subsequently, 70 mL of water was added, collecting the floating material 12 hours later. The measurements were performed in a spectrophotometer at 600nm using a standard saccharose curve at 0, 10, 20, 30, 40 and 50 mg mL^{-1}.

To analyze and compare SOC content amongst EE, it was necessary to set the soil mass in 1000 t soil ha^{-1} (Ellert *et al.*, 2002), expressing the values in t C per 10^3 t of soil ha^{-1} (t C ha^{-1}), which eliminated the distortions produced in the calculation due to bulk density variations at each depth layer.

The SOC content at the EE level was determined using the weighting of the Espinal coverage values (Table 1).

Statistical Analysis

The results were submitted to a variance analysis (ANOVA) and the multiple Tukey test was used to compare the averages at a significance level of 5%.

RESULTS AND DISCUSSION

Soil carbon stock in a gradient vegetation coverage of the Espinal ecosystem

Native forest presented a C storage capacity of 136 t ha^{-1} (sum of the C stock in the profile), which is significantly greater ($p \leq 0.05$) than that found for the rest of EE (Table 2).

Native forest included the original deciduous vegetation of *Maytenus boaria* Mol, *Quillaja saponaria* Mol., *Shinus polygamus* Cav., *Peumus boldus* Mol., *Lithrea caustica* Mol, *Cryptocarya alba* Mol. and *A. caven*, which possess a great naturalist value because these vegetation represents one of the few remaining vestiges of the original vegetation of Mediterranean Chile. The greatest C stock was found in WPE and GE (70 and 68 t C ha^{-1} respectively) with no significant difference ($p \leq 0.05$) between them; the lowest storage levels was found in DE and VDE (36 and 42 t C ha^{-1}, respectively) with no significant difference ($p \leq 0.05$).

Espinal ecosystem coverage is related to the development of last change in land-uses in the past. Sites with few trees coverage are associated to more intensive use for agricultural practices; for instance, less than 25 % coverage is associated to EE of 30 years old and intensive use with annual cereal and legume crops. On the other hand EE coverage upper 50 % are associated with less soil intervention and tree of about 90 years old (Ovalle *et al.*, 2006). This EE with less coverage has less aerial and root development resulting in lower soil input of organic material giving low SOC content.

Distribution of soil carbon stock in the profile

Large differences were observed between under canopy (Figure 1) and intercanopy (Figure 2) in all depth. NF showed 73 % more SOC under canopy than intercanopy at 0-5 cm soil depth. Soil organic C of NF was significant greater than the other EE, except for intercanopy ecosystem and for soil depth. The differences amongst EE were notorious when it was a clear cut in

Table 2: Average of SOC (t C ha^{-1}) for both under canopy and intercanopy soil samplings in the Chilean Mediterranean Espinal ecosystem (NF = Native forest; WPE = well preserved Espinal; GE = Good Espinal; DE = Degraded Espinal; VDE = Very degraded Espinal). Error bars indicate one standard error of the mean (n = 8). Different letters in the columns indicate statistical difference between soil depths (Tukey Test, $p \leq 0.05$).

Cuadro 2: Promedio de SOC (t C ha^{-1}) para las muestras de suelo bajo canopia e intercanopia en los ecosistemas de Espinal de Chile Mediterráneo (NF = Bosque nativo; WPE = Espinal bien preservado; GE = Espinal bueno; DE = Espinal degradado; VDE = Espinal muy degradado). Barras de error muestran error estándar respecto al promedio (n = 8). Letras distintas denotan diferencia significativa (Test de Tukey, $p \leq 0.05$).

	------------------- SOC stock (t C ha^{-1})-----------------				
Depth	NF	WPE	GE	DE	VDE
0 -5	67.73 ± 3.58 a	31.70 ± 1.44 b	28.50 ± 2.32 b	13.05 ± 0.65 c	12.73 ± 0.89 c
5 -10	37.48 ± 2.42 a	17.07 ± 1.58 b	17.31 ± 1.48 b	8.15 ± 0.34 c	9.57 ± 0.63 c
10-20	19.31 ± 1.73 a	13.86 ± 1.99 ab	11.64 ± 0.77 bc	7.97 ± 1.06 c	10.89 ± 0.75 bc
20-40	11.02 ± 1.18 a	7.62 ± 0.84 bc	10.47 ± 0.66 ab	6.81 ± 0.92 c	8.71 ± 0.35 abc
Total	135.54	70.25	67.92	35.97	41.90

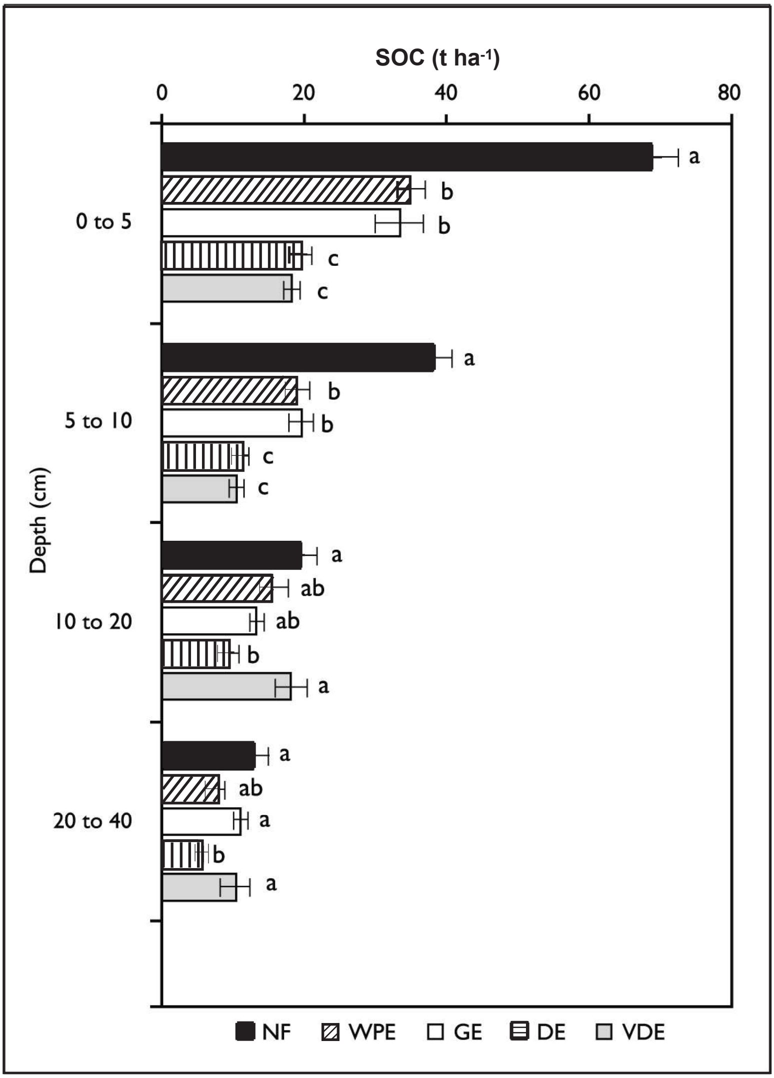

Figure 1: SOC stock (t ha^{-1}) under canopy of *A. caven* in the Mediterranean ecosystems of Chile. (NF = Native forest; WPE = well preserved Espinal; GE = Good Espinal; DE = Degraded Espinal; VDE = Very degraded Espinal). Error bars indicate one standard error of the mean (n = 8). Different letters indicate significant difference (Tukey Test, $p \leq 0.05$).

Figura 1: Almacenamiento de SOC (t ha^{-1}) bajo canopia de *A. caven* en los ecosistemas Mediterráneos de Chile. (NF = Bosque nativo; WPE = Espinal bien preservado; GE = Espinal bueno; DE = Espinal degradado; VDE = Espinal muy degradado). Barras de error muestran error estándar respecto al promedio (n = 8). Letras distintas denotan diferencia significativa (Test de Tukey, $p \leq 5$).

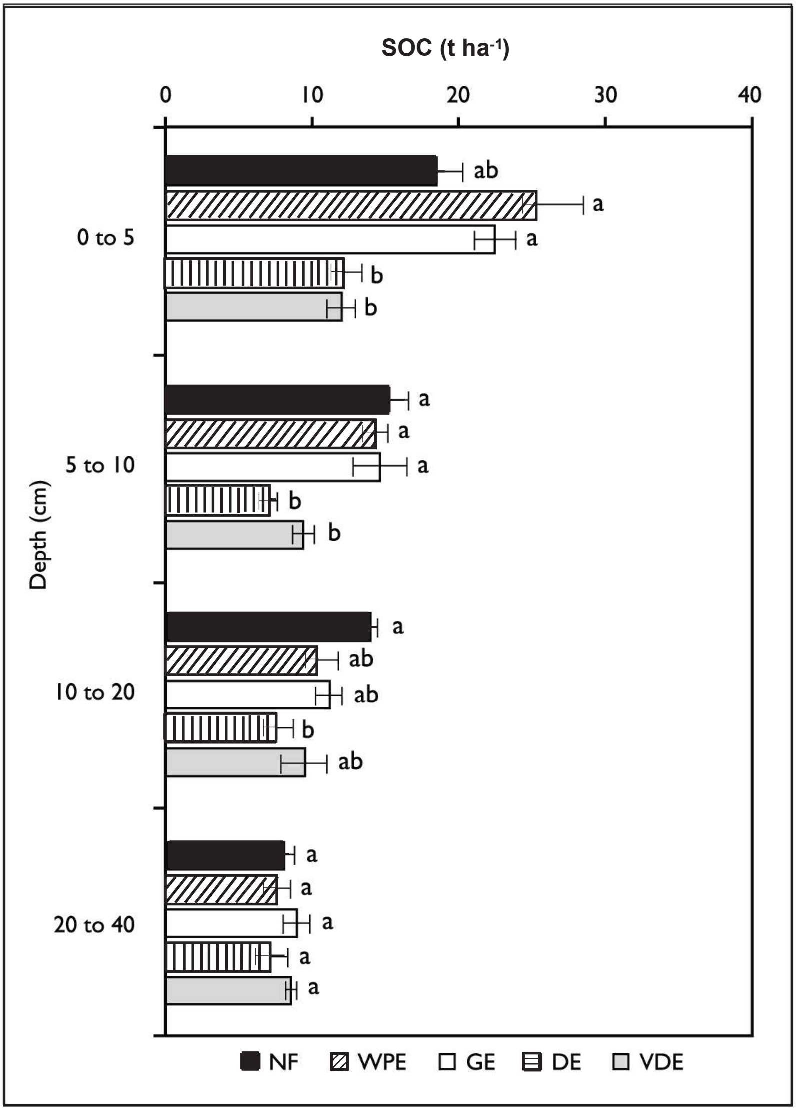

Figure 2: SOC stock (t ha^{-1}) for intercanopy of *A. caven* in the Mediterranean ecosystems of Chile. Ecosystems description as is in Figure 1. Error bars indicate one standard error of the mean (n = 8). Different letters to show significant difference (Tukey Test, $p \leq 0.05$). Note different scale.

Figura 2: Almacenamiento de SOC (t ha^{-1}) entre-canopia de *A. caven* en los ecosistemas de la zona Mediterránea de Chile. Descripción de ecosistemas tal como en Figura 1. Barras de error muestran error estándar respecto al promedio (n = 8). Letras distintas denotan diferencia significativa (Test de Tukey, $p \leq 5$). Notar diferente escala.

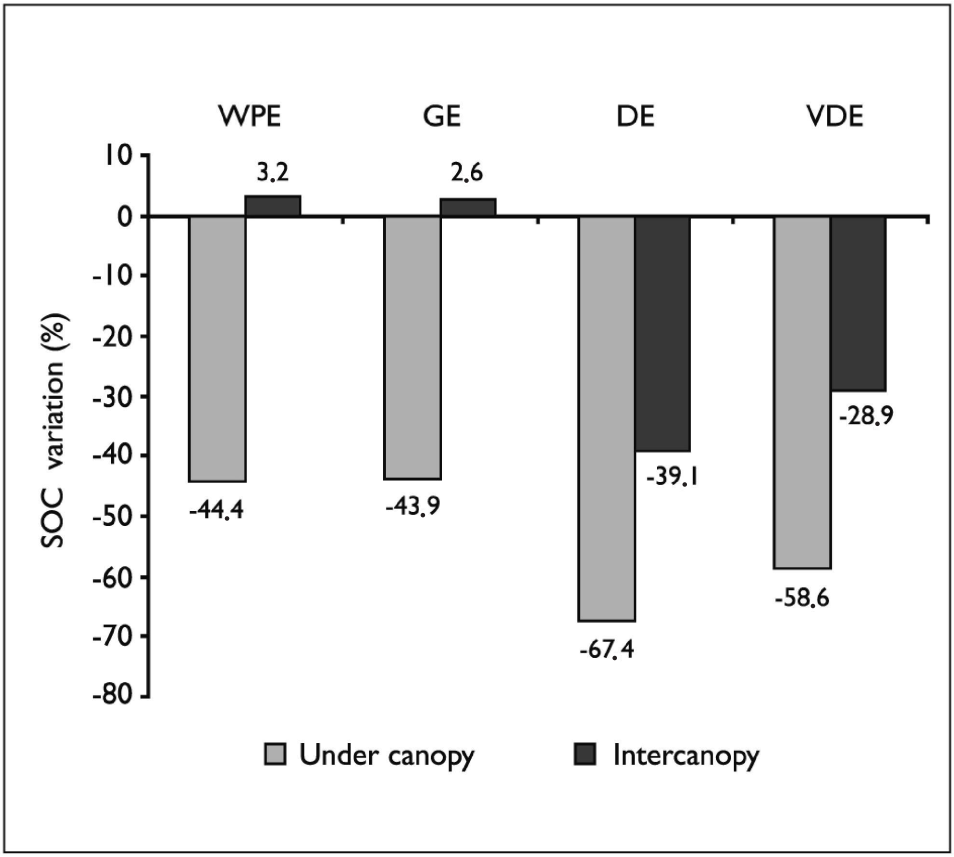

Figure 3: SOC variation (%) in the gradient of *A. caven* with respect to native forest (NF) ecosystem, 0-40 cm of depth. Ecosystems description as is in Figure 1.
Figura 3: Variación de SOC (%) en el gradiente de *A. caven* respecto al ecosistema de bosque nativo (NF), profundidad 0-40 cm. Descripción de ecosistemas tal como en Figura 1

degradation criteria, sampling distance and soil depth. On average, there was approximately 25 % more C under the tree canopy than outside of it. For instance, SOC loading between WPE and GE under canopy were not significant at 0-5 cm and 5-10 cm. The same pattern was observed for GE and DE. However, there were significant differences between these two groups. These results were less clear when the soils were sampled outside of the canopy and within the profile. In all cases SOC stock decreased with the soil depth. For NF SOC was about 68 t ha^{-1} at 0-50 cm and declined about 11 t ha^{-1} for 20-40 cm depth. The same pattern was observed for the rest coverage land criteria. The results of the present work show that when *A. caven* diminishes their soil coverage from 80 to 50 % there was no significant reduction in SOC content in the first layer. However, when it diminishes between 25 to 50 %, SOC stock at 40 cm is reduced to near 40 %. The differences observed are attributed to the contribution of litter fall, fine root dynamics and the edaphic structure. In contrast, in more degraded EE (DE and VDE), SOC levels are more homogenous within the profile. Outside the canopy and poor coverage of *A. caven* results in a low quantity of residues input from both the woody tree and understorey herbaceous vegetation. Ovalle *et al*. (2006) indicated that the prairie that co-exist with the tree in EE, such as *Lolium multiflorum, Briza máxima and Avena barbata*, are more productive and higher quality species for grassing animals than in the species outside of *A. caven* canopy. In the soils intercanopy, the C level was similar throughout the profile, mainly in VDE which presented an average of 10 t C ha^{-1}. Conclusive results with respect to this fact were reported by Davenport *et al,* (1996) when studying C content in soils under species of the *Juniperus* and *Pinus* genera in the semi-arid region of Western United States. They found that the SOC content in intercanopy spaces did not present profile variations, while soils under canopy presented organic (O) horizon accumulations. These results confirmed that litter fall is important C input to form the O horizon under canopy, while intercanopy soils do not. Additionally, Davenport *et al,* (1996) demonstrated morphological differences in the soils between under and intercanopy conditions, attributing the differences exclusively to the erosion process occurring in intercanopy sites due to the lack of vegetation that could intercept precipitation in the unprotected soil.

Figure 3 present the variation of C in the gradient of EE in all profile (0-40 cm). Reduction in C storage for WPE was about 44 % with respect to NF and for DE was 67 %. The canopy's influence on the soil's chemical characteristics in semi-arid ecosystems had been studied earlier by several authors (Belsky *et al*, 1993, Scholes and Archer, 1997, Geesing *et al.*, 2000), who have referred to these sectors as “islands of fertility”.

Some of the authors indicate that there is a redistribution of nutrients from lower depths towards the surface, while others indicate that it results from a direct contribution from the tree. Geesing *et al* (2000) determined that C, N, P (phosphorous) content increased in soil under *Prosopis* sp. canopy in site with old tree (more trunk diameter).

The increase of C stock under *A. caven* canopy was higher than results of Hagos and Smith (2005) in soils under *A. mellifera* in a semi-arid ecosystem of southern Africa. They reported an increase in SOC content at 0-20 cm in the following order: intercanopy, under canopy, and near the trunk, 0.60 %, 0.64 % and 0.82 % SOC, respectively. In our study we observed the same pattern but with highest increase of SOC at the top layer attributed to climatic conditions and soil properties.

The results of the present study indicate that *A. caven* makes a relevant contribution in SOC accumulation under canopy. According to Muñoz *et al.* (2006) these increase microbial biomass and microbial activity, suggesting an increase in soil fertility levels. The large contribution of SOC under canopy is quite surprising despite of low productivity of this specie and its low proportion of easily decomposable materials in the litter (only 7 % of total mass are leaves) (Aronson *et al*, 2002). Other studies have argued that *Faidherbia albida* (Dancette and Poulain, 1969) and *Prosopis* sp. (Geesing *et al*, 2000) have positive effects on soil fertility as well.

Diverse studies performed in soils under semi-arid climatic conditions (Geesing *et al.*, 2000, Ganry *et al.*, 2001, Almendros and Zancada, 2005, García *et al.*, 2005) indicated the possibility of reverting SOC losses that depends on changes in management strategies because some practices lead to erosive processes due to vegetation removal, intensive planting, and frequent burnings of residual vegetation. In the present study *A. caven* offers a positive impact on soil C stocks in a Chilean Mediterranean Alfisol in which conservative management would considerably improve C levels, reverting soil degradation processes in these vulnerable Espinal ecosystems.

CONCLUSIONS

The beneficial effect of the *A. caven* in Mediterranean ecosystems in Chile was demonstrated by the increase in SOC stock in the profile (0-40 cm) under canopy. The coverage degree of *A. caven* affected directly the C stock, decreasing it when the tree coverage diminished and soil use intensity increased.

A. caven in the Chilean Mediterranean zone presented an elevated potential to increase soil C lodging under canopy, where more conservationist management together with rehabilitation of extensive Chilean surfaces area that make the Espinal ecosystem a potential C sink, contributing to mitigate the impact of atmospheric CO_2 and greenhouse effects.

ACKNOWLEDGEMENTS

We thank at Fondecyt Grant (1030883), Bicentenary Program of Science and Technology, CONICYT-World Bank-Universidad de Concepción and Doctoral Program in Natural Resource Sciences of Universidad de La Frontera. We are indebted to Dr. Francisco Matus, Associated Editor of this Journal for their valuable comments and English corrections.

REFERENCES

ALMENDROS, G., ZANCADA, M.C, PARDO, M.T. 2005. Land use and soil carbon accumulation patterns in South African savanna ecosystems. Biology and Fertility of Soils 41:173-181.

ARONSON, J. 1992. Evolutionary biology of *Acacia caven* (Leguminosae, Mimosoideae): infraspecific variation in fruit and seed characters. Annals of the Missouri Botanical Garden 79:958–968.

ARONSON, J., OVALLE, C., AVENDAÑO, J., LONGERI, L., DEL POZO, A. 2002. Agroforestry tree selection in central Chile: biological nitrogen fixation and early plant growth in six dryland species. Agroforestry Systems 56:155-166.

ARROYO, M.T., CAVIERES, L. 1997. The Mediterranean-type climate flora of central Chile: What we do know and how can we assure its protection, in G. Montenegro, B.T. Timmermann: Taller internacional sobre aspectos ambientales, ideológicos, éticos y políticos en el debate sobre bioprotección y uso de recursos genéticos en Chile. Noticiero de Biología N° 5, p. 48-56.

BELSKY, A.J., MWONGA, S.M., AMUNDSON, R.G., DUXBURY, J.M., ALI, A.R. 1993. Comparative effects of isolated tree on their under canopy environments in high- and low-rainfall savannas. Journal of Applied Ecology 30:143-155.

CIREN, 1994. Descripciones de suelos, materiales y símbolos. Estudio agrológico precordillera VIII región, p. 43-47.

COWLING, R.M., RUNDEL, P.W., LAMONT, B.B., ARROYO, M.K., ARIANOUTSOU, M. 1996. Plant diversity in Mediterranean-climate regions. Trends in Ecology and Evolution (Tree) 11:362-368.

DANCETTE, C., POULAIN, J.F. 1969. Influence of *Acacia albida* on pedoclimatic factors and crop yields. African Soils 14:143-184.

DAVIS S, HEYWOOD, V.H., HERRERA, O.,MACBRYDE,J., VILLALOBOS, J., HAMILTON, A.C. 1997. Centers of plant diversity: a guide and strategy for their conservation. IUCN Publications unit. Cambridge, U.K, 562 p.

DAVENPORT, D.W., WILCOX, B.P., BRESHEARS, D.D. 1996. Soil morphology of canopy and intercanopy sites in Piñon-Juniper woodland. Soil Science Society of America Journal 60:1881-1887.

ECHEVERRIA, C., COOMES, D., SALAS, J., REY-BENAYAS, J.M. LARA, A., NEWTON, A. 2006. Rapid deforestation and fragmentation of Chilean Temperate Forest. Biological conservation 130:481-494.

ELLERT, B.H., JANZEN, H.H., ENTZ, T. 2002. Assessment of a method to measure temporal change in soil carbon storage. Soil Science Society of America Journal 66:1687-1695.

GANRY, F. FELLER, C., HARMAND, J-.M., GUIBERT, H. 2001. Management of soil organic matter in semiarid Africa for annual cropping systems. Nutrient Cycling in Agroecosystems 61:105-118.

GARCIA, C., ROLDAN, A., HERNANDEZ, T. 2005. Ability of different plant species to promote microbiological processes in semiarid soil. Geoderma 124:193-202.

GEESING, D., FELKER, P., BINGHAM, R. 2000. Influence of mesquite (*Prosopis glandulosa*) on soil nitrogen and carbon development: Implications for global carbon sequestration. Journal of Arid Environments 46:157-180.

GUO, L.B., GIFFORD, R.M. 2002. Soil carbon stocks and land use change: a meta analysis. Global Change Biology 8:345-360.

HAGOS, M.G., SMITH, G.N. 2005. Soil enrichment by *Acacia mellifera* subsp *detinens* on nutrient poor sandy soil in a semi-arid southern african savanna. Journal of Arid environments 61: 47 - 59.

INSTITUTO NACIONAL DE ESTADÍSTICAS (INE). 1995. Chile. Ciudades, pueblos y aldeas, Santiago, INE, 16 p.

MONTENEGRO, G., GÓMEZ, M., DÍAZ, F., GINOCCHIO, R. 2003. Regeneration potential of Chilean matorral after fire: an update view, in Veblen et al.: Fire and climatic change in temperate ecosystems of the western Americas. Ecological studies 160, Springer, p. 381-409.

MUÑOZ, C. 2006. Dinámica del carbono orgánico del suelo en ecosistemas de la zona Mediterránea de Chile. Tesis de Doctorado en Ciencias de Recursos Naturales, Universidad de La Frontera, Chile. 123 p.

MUÑOZ, C., ZAGAL, E., OVALLE, C. 2006. Influence of tree on soil organic matter in Mediterranean agroforestry systems: an example from the 'Espinal' of central Chile. European Journal of Soil Science. DOI: 10.1111/j.1365-2389.2006.00858.x. In press.

OVALLE, C., ARONSON, J, DEL POZO, A., AVENDAÑO, J. 1990. The Espinal: agroforestry systems of the Mediterranean-type climate region of Chile: State of art and prospects for improvement. Agroforestry Systems 10:213-239.

OVALLE, C., LONGERI, L., ARONSON, J., HERRERA, A., AVENDAÑO, J. 1996. Atmospheric N_2-fixation, nodule efficiency and biomass accumulation after two years in three Chilean legume trees and Tagasaste (*Chamaecytisus proliferus* subsp. palmensis). Plant and Soil 179:131-140.

OVALLE, C., ARONSON, J., DEL POZO, A., AVENDAÑO, J. 1999. Restoration and rehabilitation of mixed espinales of central Chile. Arid Soil Research and rehabilitation 13:369-381.

OVALLE, C., DEL POZO, A., CASADO, M.A., ACOSTA, B., DE MIGUEL, J.M. 2006. Consequences of Landscape Heterogeneity on Grassland Diversity and Productivity in the Espinal Agroforestry System of Central Chile. Landscape Ecology 21:585-594

SANTIBÁÑEZ, F., URIBE. J.M. 1993. Atlas agroclimático de Chile. Ministerio de Agricultura, Fondo de Investigación Agropecuaria, Santiago, Chile, 99 p.

SCHOLES, R.J., ARCHER, S.R. 1997. Tree-grass interactions in savannas. Annual Review Ecology and Systematic 28:517-544.

SIMS, J.R., HABY, V.A. 1971. Simplified colorimetric determination of soil organic matter. Soil Science 112:137-141.

STOLPE, N.B. 2006. Grupo de suelos graníticos. Descripciones de los principales suelos de la VIII Región de Chile. Publicaciones del Departamento de Suelos y Recursos Naturales. Facultad de Agronomía.Universidad de Concepción, Chile, p. 48-52.