

## Soil organic carbon and dead biomass pools in woodlands from Monte region (Argentina)

Reservorios de carbono orgánico del suelo y biomasa muerta  
en áreas forestales de la región Monte (Argentina)

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### SUMMARY

Soil and above-ground dead biomass are important carbon pools in drylands. They depend on local controls and patterns that should be studied. The objective of this work is to understand and quantify the influence of the vegetation canopy in the regulation of soil and dead biomass carbon stocks in woodlands of Monte region in Argentina. The hypothesis is that soil and dead biomass carbon stocks are lower in the intercanopy and higher under the canopy, independently of the type of canopy. Thirty sampling plots were selected, identifying three treatments: tree canopy, intercanopy and shrub canopy. In each sampling plot, soil and dead biomass were sampled. Four physiognomic-functional groups were identified. *Prosopis* woodlands accumulated about 38 Mg ha<sup>-1</sup> of dead organic carbon (from soil, litter, and dead wood), followed by *Suaeda* woodlands with almost 35 Mg ha<sup>-1</sup>. Mixed woodlands showed average values around 27 Mg ha<sup>-1</sup>, while *Bulnesia* woodlands around 25 Mg ha<sup>-1</sup>. The vegetation canopy, and consequently, litter and dead wood input affected soil organic carbon in topsoil. Shrubs such as *Larrea* spp. had a restricted ability to enrich soil compared to *Prosopis* spp. Soil, litter and dead wood are significant pools of carbon and should be included in programs on reducing emissions in arid regions. The hypothesis is accepted partially; there is a remarked contrast in carbon content between soils under the tree canopy and off the canopy. However, the effect of shrub canopy is intermediate between both treatments.

*Key words:* litter, shrub, tree canopy, dead wood.

### RESUMEN

El suelo y la biomasa muerta son importantes reservorios de carbono en zonas áridas. Ellos dependen de patrones y factores locales que deben ser estudiados. El objetivo de este trabajo fue cuantificar la influencia del dosel de la vegetación en los contenidos de carbono del suelo y de la biomasa muerta en áreas forestales de la región Monte en Argentina. La hipótesis es que los contenidos de carbono en el suelo y en la biomasa muerta son menores fuera del dosel y mayores bajo dosel, independientemente del tipo de dosel. Treinta parcelas de muestreo fueron seleccionadas, identificando tres tratamientos: bajo dosel arbóreo, espacio sin dosel y bajo dosel arbustivo. Se muestrearon suelo y biomasa muerta. Se identificaron cuatro grupos fisiognómico-funcionales. Los bosques de *Prosopis* spp. acumularon ~ 38 Mg ha<sup>-1</sup> de carbono orgánico muerto (suelo, mantillo y madera muerta), las áreas forestales de *Suaeda* spp. ~ 35 Mg ha<sup>-1</sup>, los bosques mixtos ~ 27 Mg ha<sup>-1</sup> y los bosques de *Bulnesia* spp. ~ 25 Mg ha<sup>-1</sup>. El dosel de la vegetación y, consecuentemente, los aportes de mantillo y madera muerta influyeron en los contenidos de carbono del suelo superficial. Arbustos como *Larrea* spp. tienen menor capacidad para enriquecer el suelo que *Prosopis* spp. El suelo, mantillo y madera muerta son reservorios significativos de carbono y deberían ser considerados en programas de reducción de emisiones en zonas áridas. La hipótesis fue parcialmente aceptada; hay un marcado contraste en los contenidos de carbono entre suelos bajo y fuera del dosel. Sin embargo, el efecto del dosel arbustivo es intermedio entre ambos tratamientos.

*Palabras clave:* mantillo, arbusto, canopia arbórea, madera muerta.

### INTRODUCTION

Soils are an important carbon sink in ecosystems worldwide. Trees, shrubs and herbs can assimilate CO<sub>2</sub> from the atmosphere and transform it into biomass. Some of above-ground or subterranean tissues may be assimila-

ted into the soil profile, enriching it with organic carbon. Carbon stocks in ecosystems are the result of the balance between the rates of accumulation and decomposition.

Accumulation rates depend on the net primary production of vegetation, which in turn depends on solar radiation, air temperature, nutrients and water, needed for

plants to grow (Jobbágy and Jackson 2000). Plants physiology and architecture, *e.g.*, deciduousness or canopy volume, also affect carbon accumulation. Decomposition rates depend on soil characteristics and the microclimate under the canopy.

Plants in arid lands have a restricted growth due to harsh environmental conditions such as scarcity of water and nutrients. Only adapted species can develop under arid and hyperarid conditions, and they usually grow in communities within fertile small-scaled patches. Woody plants in arid zones are the primary microclimate regulators, not only by attenuating drastic changes in air temperature and humidity, but also altering soil conditions under the canopy (Rossi and Villagra 2003).

Soil is the most abundant organic carbon pool in the terrestrial biosphere, compared to vegetation and animals. Although many authors studied soil organic matter and litter carbon contents in natural ecosystems (Yang *et al.* 2007), and specifically in arid zones (Charley and West 1975, Rossi and Villagra 2003), local controls should be studied more thoroughly (Yang *et al.* 2007). Such local controls are defined by local climate, soil type and dominant vegetation.

Covering about 47 % of the total terrestrial surface, drylands hold 27 % of the global soil organic carbon reserves (Trumper *et al.* 2008). Desertification may reduce such carbon reserves. With 50,678,905 ha (Karlin *et al.* 2017), Monte region represents 18 % of the total continental area of Argentina, being an important carbon sink due to its extension. It also holds some biogeographic similarities with other regions of South America, North of Mexico and South of the USA (Roig *et al.* 2009). The study of soil carbon stocks in this region might produce relevant information for ecosystem management and conservation practices in arid zones, *e.g.*, for plants arrangement within agroforestry experiences.

The objective of this work is to understand and quantify the influence of the vegetation canopy in the regulation of soil and dead biomass carbon contents in woodlands of Monte region in Argentina. Since the influence of shrubs on carbon inputs is poorly understood, they were compared with the tree canopy effect. The amounts of carbon accumulated in the soil, litter and dead wood in Monte woodlands have been quantified, considering three different treatments: under tree canopy, under shrub canopy and intercanopy.

The hypothesis is that independently of the type of canopy (trees or shrubs; deciduous or semideciduous), the soil, litter and dead biomass carbon stocks in woodlands of Monte region are lower in the intercanopy and higher under the canopy.

## METHODS

*Study area.* Monte region is an extended area of about 50 million ha, stretched along 21° of latitude (23°12' to 44°20' S)

at the east of the Andes, and it is the most arid rangeland in Argentina. The elevation ranges between 0 and 3,000 m above sea level (Karlin *et al.* 2017). Water table depth is variable, nonetheless it is usually shallow in forest areas within valleys. The primary soil use is for forestry of native species and extensive livestock of variable intensity. Monte region can be divided into two districts, according to its dominant topography: Southern Monte (of plains and plateaus) and Northern Monte (of mountains and valleys), limiting at 32°50' S latitude (Morello 2012). Despite its extension, the climate, physiognomy and floristic composition, it is relatively homogeneous. Nevertheless, soil features are highly diversified due not only to soil genesis but to anthropic effects such as logging and overgrazing, inducing erosion. Southern Monte is a sandy plain of quaternary fluvial, lacustrine and aeolian origin. Northern Monte is a mountainous area furrowed by intermittent rivers shaping the relief, in which margins the vegetation makes use of the resulting moisture, sometimes resulting in dense forests (Abraham *et al.* 2009).

The climate is arid, with high evapotranspiration rates. Mean annual rainfall varies between < 100 and 450 mm, concentrated in summer, and it is strongly conditioned by topography. Mean annual temperature varies between 10 and 18 °C; the lowest means occur in Northern Monte, with topography-dependent isotherms (Abraham *et al.* 2009). Monte region is a steppe dominated by shrublands of *Larrea* spp. intertwined with open or closed patches of *Prosopis* spp., *Geoffroea decorticans* (Gillies ex Hook. *et* Arn.) Burkart, and *Bulnesia retama* (Gillies ex Hook. *et* Arn.) Griseb, (among other species) tree communities. The main species living in Monte region are condensed in table 1, based on Flores *et al.* (2015) and Oyarzábal *et al.* (2018).

The sampling plots were located according to the sampling grid design for the Second National Inventory of Native Forests (Strada *et al.* 2011), consisting of 10 km equidistant points. Sampling plots presenting more than 20 % of tree cover and average height up to 3 m (Argentinian Federal Council for the Environment 2012) and ease of access using 4x4 vehicle and within 2 km by foot from the vehicle were also selected. According to these criteria, 30 sampling plots were selected within Monte region (figure 1), ten from Southern Monte and 20 from Northern Monte. Samplings were made between July and November of 2018, during the dry and windy season.

*Physiognomic-functional traits classification.* In each sampling plot, a plant characterization was made by the phytosociological method (Braun-Blanquet 1979). The sampled area was defined by a radius of 20 m from the central point of the sample plot. Values of cover-abundance of all present plant species were transformed into percent cover values based on the midpoint of each value on the scale (Braun-Blanquet 1979).

With this data, a physiognomic-functional classification of the surveyed woodlands was obtained through con-

glomerate and discriminant analyses. This classification defined environments with different carbon dynamics.

*Sampling design.* In each sampling plot, 20 m long transects were located towards the four cardinal directions (north, south, east, west). Over each transect, two sites

were selected as different treatments: under tree canopy (UT) and intercanopy (IC) (figure 2). When any of the described treatments were not present along a transect, samples were taken under shrub canopy (US). A tree is defined as a woody, perennial plant species when over 3 m tall, with one or multiple trunks differentiated from the

**Table 1.** List of the main species living in Monte region.

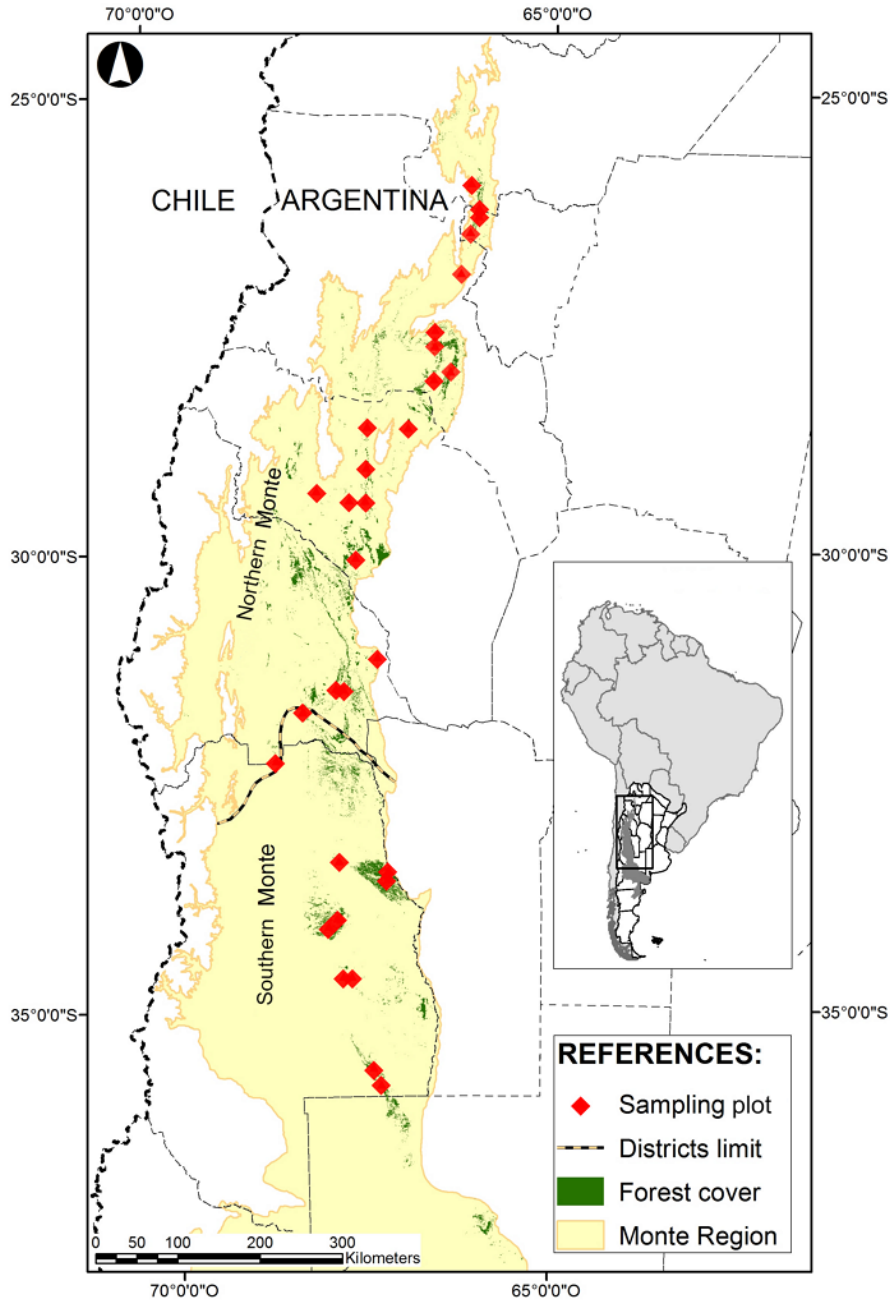
Lista de las principales especies que viven en la región del Monte.

Family	Species	Habit
Asteraceae	<i>Baccharis salicifolia</i> (Ruiz <i>et</i> Pav.) Pers.	Shrub
Asteraceae	<i>Chuquiraga erinacea</i> D. Don	Shrub
Capparaceae	<i>Atamisquea emarginata</i> Miers ex Hook. <i>et</i> Arn.	Shrub or tree
Celastraceae	<i>Maytenus viscifolia</i> Griseb.	Tree
Chenopodiaceae	<i>Allenrolfea vaginata</i> (Griseb.) Kuntze	Shrub
Chenopodiaceae	<i>Atriplex lampa</i> (Moq.) D. Dietr.	Shrub
Chenopodiaceae	<i>Suaeda divaricata</i> Moq.	Shrub
Euphorbiaceae	<i>Jatropha excisa</i> Griseb.	Shrub
Fabaceae	<i>Vachellia aroma</i> (Gillies ex Hook. <i>et</i> Arn.) Seigler <i>et</i> Ebinger	Shrub or tree
Fabaceae	<i>Senegalia gilliesii</i> (Stued.) Seigler <i>et</i> Ebinger	Tree
Fabaceae	<i>Parkinsonia praecox</i> (Ruiz <i>et</i> Pav. ex Hook.) Hawkins	Shrub
Fabaceae	<i>Geoffroea decorticans</i> (Gillies ex Hook. y Arn.) Burkart	Tree
Fabaceae	<i>Prosopis alpataco</i> Phil.	Shrub
Fabaceae	<i>Prosopis chilensis</i> (Molina) Stuntz emend. Burkart	Tree
Fabaceae	<i>Prosopis flexuosa</i> DC.	Tree
Fabaceae	<i>Prosopis strombulifera</i> (Lam.) Benth. var. <i>strombulifera</i>	Shrub
Fabaceae	<i>Zuccagnia punctata</i> Cav.	Shrub
Fabaceae	<i>Parasenegalia visco</i> (Lorentz ex Griseb.) Seigler <i>et</i> Ebinger	Tree
Nyctaginaceae	<i>Bougainvillea spinosa</i> (Cav.) Heimerl	Shrub
Plantaginaceae	<i>Monttea aphylla</i> (Miers) Benth. y Hook.	Shrub
Poaceae	<i>Aristida mendocina</i> Phil.	Grass
Poaceae	<i>Jarava ichu</i> Ruiz <i>et</i> Pav.	Grass
Poaceae	<i>Leptochloa crinita</i> (Lag.) P.M. Peterson <i>et</i> N.W. Snow	Grass
Salicaceae	<i>Salix humboldtiana</i> Willd.	Tree
Solanaceae	<i>Lycium boerhaviaefolium</i> L. f.	Shrub
Solanaceae	<i>Lycium chilense</i> Miers ex Bertero	Shrub
Ximeniaceae	<i>Ximena americana</i> L.	Shrub or tree
Zygophyllaceae	<i>Bulnesia retama</i> (Gillies ex Hook. <i>et</i> Arn.) Griseb.	Shrub or tree
Zygophyllaceae	<i>Larrea cuneifolia</i> Cav.	Shrub
Zygophyllaceae	<i>Larrea divaricata</i> Cav.	Shrub
Zygophyllaceae	<i>Larrea nitida</i> Cav.	Shrub
Zygophyllaceae	<i>Plectrocarpa tetraacantha</i> Gillies ex Hook. <i>et</i> Arn.	Shrub

crown. A shrub is defined as a woody, perennial plant species when under 3 m tall, according to Guideline #1.2 Res. 230/12 of the Argentinian Federal Council for the Environment (COFEMA 2012), with the crown undifferentiated from the trunk. In each treatment, the tree and shrub species were identified.

The woody species were classified into two groups, according to deciduousness. Deciduous species are those losing their vegetative or reproductive tissues along a pe-

riod larger than six months without significant seasonality effects. Semideciduous species are those losing their vegetative or reproductive tissues sporadically or concentrated in only one season. The last group includes those species considered as aphyllous. The deciduous species are represented by *Prosopis* spp., *Geoffroea decorticans*, *Mimozyanthus carinatus*, *Atamisquea emarginata*, *Plectrocarpa tetracantha*, *Vachellia aroma*, and *Allenrolfea* spp. (the last by the release of their strobiles). The semideciduous



**Figure 1.** Sampling area in Monte region. ♦: Sampling plots. Dark (green) areas: Forest cover.

Área de muestreo en la región Monte. ♦: Parcelas de muestreo. Áreas oscuras (verde): Cobertura forestal.

species are represented by *Bulnesia retama*, *Larrea* spp., *Condalia microphylla*, and *Suaeda divaricata*.

Along each transect, plant cover was measured as the projection of the crown, defining tree and shrub cover in percent. The sectors without crown projection along the transects were identified as intercanopy. In each site, a quadrat of 0.25 m<sup>2</sup> was placed to delimit the area for soil and litter sampling. Over each transect, a strip of 10 x 2 m was defined to measure the dead wood presenting more than 5 cm diameter (figure 2).

**Soil bulk density.** A 7 cm diameter and 7 cm height Kopecky cylinder was used to extract undisturbed soil samples for bulk density measurement. The most representative transect in each sample plot was selected, resulting in four soil samples per sample plot: under tree canopy and intercanopy (or under shrub canopy) at 0-7 cm depth and 10-17 cm depth.

Soil samples were carefully pulverized without losing any material and air-dried at 60 °C in a forced-air chamber for three days and weighed. The soil bulk density was the result of the ratio between the dry weight of the sample and the cylinder volume. When soil samples could not be extracted due to the presence of rocks and gravel, soil bulk density was estimated according to its texture, determined by feel analysis (Thien 1979).

With the soil bulk density, soil mass (*SM*) in Mg ha<sup>-1</sup> was determined for each sample plot, depth and treatment.

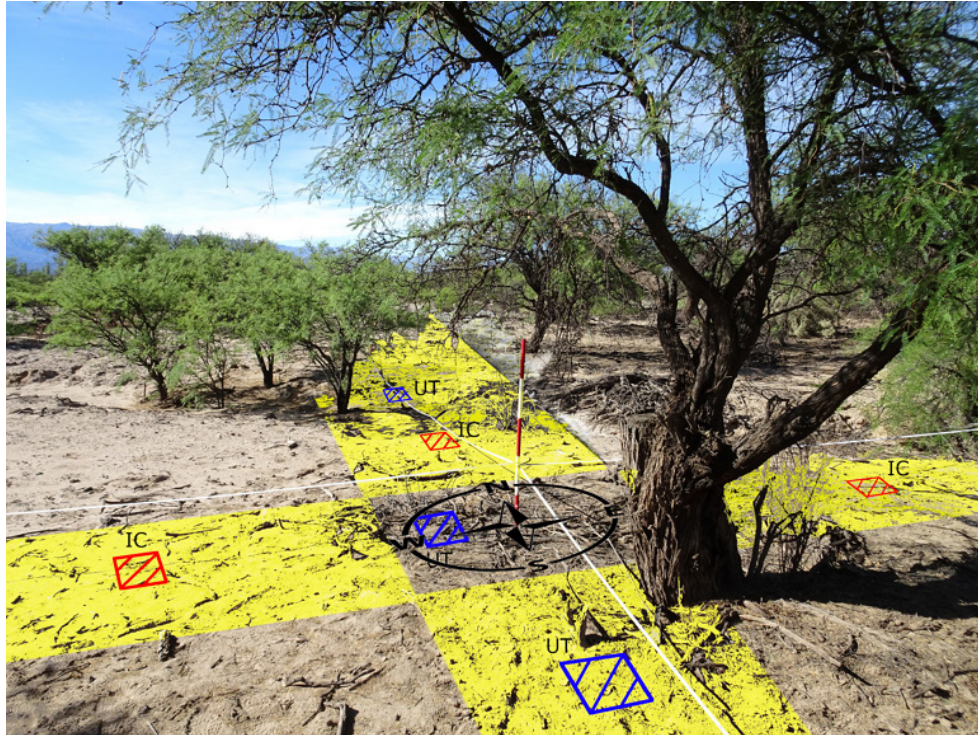
**Soil organic carbon stocks.** In each site (under tree canopy and intercanopy –or under shrub canopy–) of each transect, soil samples were taken at 0-5 cm and 5-20 cm depth, following the results of Charley and West (1975). Significant differences in arid soil organic carbon content between these layers were noted. In 20 sites, topsoil samples could not be taken due to the presence of rocks and gravel. In three sample plots from Northern Monte, no 5-20 cm depth samples were taken in any transect for the same reason.

Soil samples were pulverized, sieved and air-dried at 60 °C in a forced-air chamber for three days. Soil organic carbon content (%C<sub>s</sub>) was determined by the method of Walkley and Black (Nelson and Sommers 1974).

Once %C<sub>s</sub> was determined, soil organic carbon stock (C<sub>s</sub>) was calculated in Mg ha<sup>-1</sup> at the *i*<sup>th</sup> depth, for the *j*<sup>th</sup> treatment:

$$C_{s(i,j)} = SM_{(i,j)} * \%C_{s(i,j)} / 100 \quad [1]$$

For the determination of soil organic carbon stock per hectare, weighted by the cover (C<sub>sW</sub>), for each sample plot



**Figure 2.** Sampling design for each sampling plot. Lighted strips: 10 x 2 m strips for measuring the volume of dead wood with diameter > 5 cm; UT quadrats: under tree canopy treatment; IC quadrats: intercanopy treatment. Photo: R. Zapata.

Diseño del muestreo en cada parcela. Fajas claras: bandas de 10 x 2 m para la medición de volúmenes de madera muerta de diámetro > 5 cm; cuadrantes UT: tratamiento bajo canopia arborea; cuadrantes IC: tratamiento de intercanopia. Foto: R. Zapata.

at the  $i^{th}$  depth and the  $j^{th}$  treatment, the following calculation was made:

$$C_{sW(i,j)} = \sum_j \left( \frac{\sum_n (C_{sn} * Cob)}{n} \right)_i \quad [2]$$

where  $\frac{\sum_n (C_{sn} * Cob)}{n}$  is the average value (Mg ha<sup>-1</sup>) of the  $n$  repetitions for the  $C_s$  values, weighted by the canopy percentage.

**Litter carbon stocks.** In each quadrat, litter and dead wood between 1 and 5 cm of diameter were collected separately. No alive grass or herbs were collected, only dead biomass. Samples were air-dried at 60 °C in a forced-air chamber for three days and weighed. From each litter sample, a subsample was extracted, weighed, minced and burned in a muffle furnace (Navarro *et al.* 1993). The muffle was preheated at 100 °C for 4 h, and afterwards the temperature was increased to 550 °C for 5 h more. The burned subsample was extracted and weighed, calculating the percentage of organic matter of the sample (%OM<sub>L</sub>) from the difference. These values were converted into carbon percentages (%C<sub>L</sub>) by using the conversion formula of Navarro *et al.* (1993):

$$\%C_L = \%OM_L * 0.51 + 0.48 \quad [3]$$

Litter carbon stock (C<sub>L</sub>) was obtained and extrapolated to an area of 1 ha by multiplying the product of litter mass (LM) and %C<sub>L</sub> by 40,000 (0.25 m<sup>2</sup> quadrats in 10,000 m<sup>2</sup>).

For the determination of the litter carbon stock in Mg ha<sup>-1</sup>, weighted by the cover (C<sub>LW</sub>) in each sample plot, the following calculation was made:

$$C_{LW(j)} = \sum_j \left( \frac{\sum_n (C_{Ln} * Cob)}{n} \right)_j \quad [4]$$

Where,  $\frac{\sum_n (C_{Ln} * Cob)}{n}$  is the average value (Mg ha<sup>-1</sup>) of the  $n$  repetitions of the  $C_L$  values, weighted by the canopy cover percentage, and  $j$  represents each treatment.

The ratio between the weighted litter carbon stocks under tree and shrub canopy was calculated for each site. This ratio was obtained as an index to quantify the influence of each cover category regarding litterfall.

**Dead wood (1 to 5 cm in diameter) carbon stocks.** The dead wood between 1 and 5 cm in diameter was collected from the quadrats and weighed. Dead wood samples originated predominantly from the species *Prosopis flexuosa* and *Bulnesia retama*. The carbon percentage (%C<sub>DW</sub>) of one sample of *P. flexuosa* and two samples of *B. retama* were analyzed by the same method and conversion formula as that of litter [3]. Navarro *et al.* (1993) demonstrated that the percentage of carbon in wood is homogeneous.

The carbon stock of the dead wood samples was obtained by multiplying the dead wood mass and %C<sub>DW</sub>.

The weighted stock (C<sub>DW<5W</sub>) in Mg ha<sup>-1</sup> of the dead wood (1-5 cm in diameter) was calculated with the same formula as that of litter [4].

**Dead wood (diameter > 5 cm) carbon stocks.** Diameter and height of the portions of dead wood branches found inside the 10 x 2 m strips were measured for volume in each quadrant. Seven to nine wood samples per species were immersed in a beaker of water that was placed on a high-precision balance, and the weight of water displacement was converted into volume (Martínez-Cabrera *et al.* 2009). Afterwards, samples were dried in a chamber of forced air at 40 °C for 48 h and weighed. The average value of wood density per species was obtained. Carbon stock (C<sub>DW>5</sub>) was obtained by multiplying dead wood mass to %C<sub>DW</sub>.

The dead wood larger than 5 cm diameter was extrapolated to one hectare. The total dead wood stock larger than 5 cm diameter (C<sub>DW>5</sub>) per each sample plot was obtained by averaging the values in Mg ha<sup>-1</sup>.

**Statistical analyses.** With the cover-abundance values, characteristic species were selected by discriminating those who had more than 3 % of the cover, on average. With these species, a conglomerate analysis (average linkage; Phi coefficient) was performed for a first tentative classification. Subsequently, with the tentative classification, a discriminant analysis was performed. A physiognomic-functional classification was finally obtained, identifying four plant clusters with different floristic characteristics.

The carbon stocks in each pool were compared between physiognomic-functional traits, treatments and plant deciduousness through ANOVA (LSD Fisher test). Simple regression analyses were made between different carbon pools. All the statistical analyses were performed with InfoStat statistical software (Di Rienzo *et al.* 2018).

## RESULTS

**Physiognomic-functional classification.** From the phytosociological analysis, 12 species were selected as characteristic species: *Prosopis flexuosa*, *Bulnesia retama*, *Lycium tenuispinosum*, *Geoffroea decorticans*, *Atamisquea emarginata*, *Larrea cuneifolia*, *Aristida adscensionis*, *Suaeda divaricata*, *Larrea divaricata*, *Jarava ichu*, *Condalia microphylla*, and *Prosopis alpataco*.

The conglomerate and the discriminant analyses defined four physiognomic-functional groups (figure 3):

- 1) Communities of *Suaeda divaricata*, co-dominated by *Prosopis flexuosa* (n = 2). They were present in mudlands, with silt loam Entisols and shallow water tables.
- 2) Mixed woodlands (n=8). Populations of *P. flexuosa*, *G. decorticans*, *L. divaricata*, and *P. alpataco* co-dominated in these woodlands. They were the dominant woody formations in the Southern Monte

district, over Entisols with loamy sand (one plot), sandy loam (five plots), loam (one plot) or silt loam (one plot) textures.

- 3) Communities of *P. flexuosa* (n = 8). *P. flexuosa* dominated, although some species such as *A. emarginata* or *G. decorticans* stood out. They were associated with Salids with loamy sand (two plots), sandy loam (three plots) or silt loam (one plot) topsoil textures, or Cambids with abundant gravel (2 plots).
- 4) Communities of *B. retama* (n = 12). Populations of *B. retama* were dominant, but *P. flexuosa* co-dominated sometimes. Their soils were diverse, from Argids or Cambids with abundant gravel and clay (two plots) to Salids (mudflats) with sandy loam (four plots) or silt loam (six plots) topsoil textures.

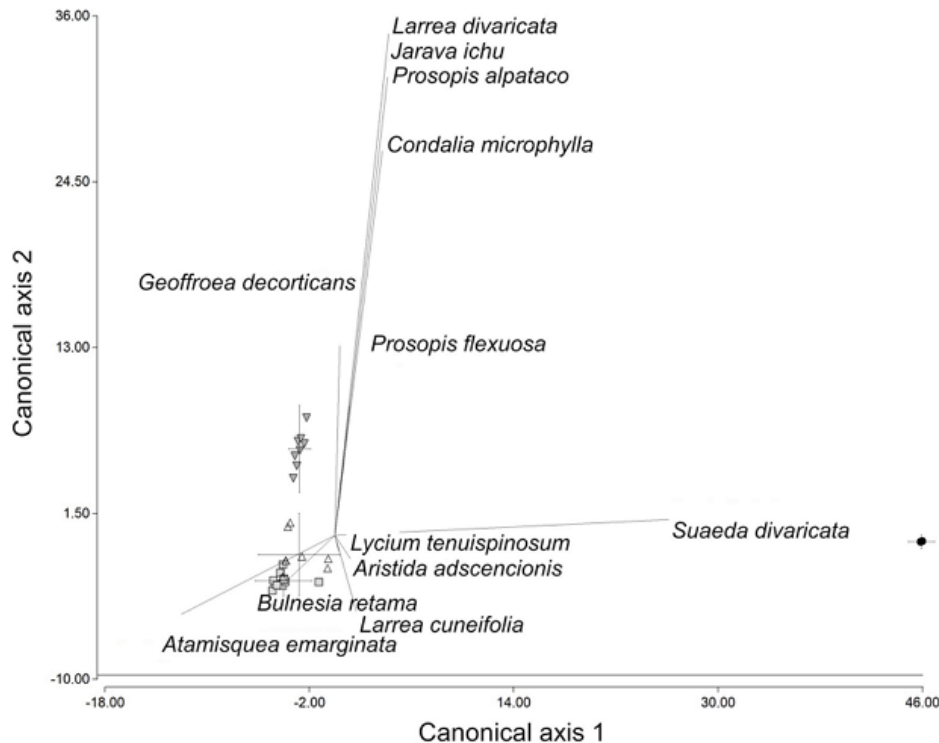
**Soil organic carbon stocks.** The soil organic carbon stock at 0-5 cm depth ( $C_{s,0-5}$ ) showed significant differences (table 2) between the intercanopy and tree canopy. The shrub canopy treatment showed no differences with the intercanopy or the tree canopy ( $F = 14.01$ ;  $P < 0.0001$ ;  $DF = 2$ ). The intercanopy had approximately half the amount of soil organic carbon than that found under tree canopy treatment. The values shown in table 2 were derived from

the following soil organic carbon percentages: IC =  $0.75 \pm 0.11$  %; UT =  $1.68 \pm 0.11$  %; US =  $1.16 \pm 0.21$  %.

The soil organic carbon stock at 5-20 cm depth ( $C_{s,5-20}$ ) was significantly lower in the intercanopy than under the tree canopy ( $F = 6.05$ ;  $P = 0.0030$ ;  $DF = 2$ ). Under shrub canopy showed no difference with either the intercanopy or the under-tree canopy treatment (table 2). The values shown in table 2 were derived from the following soil organic carbon percentages ( $\%C_s$ ): IC =  $0.61 \pm 0.07$  %; UT =  $0.99 \pm 0.07$  %; US =  $0.78 \pm 0.12$  %. Differences among treatments at 5-20 cm depth were less contrasting than those in the surface.

Soil organic carbon percentage ( $\%C_s$ ) showed significant differences between 0-5 and 5-20 cm depth under tree canopy (n = 139;  $F = 15.83$ ;  $P < 0.0001$ ), and a marginal difference ( $0.1 > P > 0.05$ ) under shrub canopy (n = 42;  $F = 3.60$ ;  $P = 0.0652$ ) and in the intercanopy (n = 143;  $F = 2.90$ ;  $P = 0.0908$ ).

When weighted by the cover percentages (table 2), soil organic carbon showed similar differences between treatments at the surface ( $F = 3.93$ ;  $P = 0.0019$ ;  $DF = 2$ ), nevertheless did not differ statistically among treatments in the deeper layer ( $F = 0.61$ ;  $P = 0.5466$ ;  $DF = 2$ ). The surveyed covered area (under tree canopy plus shrub canopy) was on average 40 % of the total surface.



**Figure 3.** Discriminant analysis, with prediction intervals associated with the four groups: ●, communities of *S. divaricata*, co-dominated by *P. flexuosa*; ▼, mixed woodlands; △, communities of *P. flexuosa*; □, communities of *B. retama*.

Análisis discriminante, con intervalos de predicción asociados a los cuatro grupos: ●, comunidades de *S. divaricata*, co-dominados por *P. flexuosa*; ▼, bosques mixtos; △, comunidades de *P. flexuosa*; □, comunidades de *B. retama*.

**Table 2.** Stocks (Mg ha<sup>-1</sup>) of soil organic carbon, litter carbon, and dead wood carbon, by treatment. IC: Intercanopy, UT: under tree canopy, US: under shrub canopy. Different letters show statistically significant differences among treatments at  $P = 0.05$ .

Contenidos (Mg ha<sup>-1</sup>) de carbono orgánico del suelo, carbono de mantillo y carbono de madera muerta, por tratamiento. IC: espacio fuera del dosel, UT: bajo dosel arbóreo, US: bajo dosel arbustivo. Letras diferentes indican diferencias estadísticamente significativas entre tratamientos al  $P = 0,05$ .

Treatment	IC	By soil cover		By deciduousness		
		UT	US	Semideciduous	Deciduous	
Soil organic carbon stock (0-5 cm depth)	n	74	72	21	27	66
	Mean	5.74 ± 0.77 (aA)	11.52 ± 0.78 (b)	8.33 ± 1.44 (ab)	8.26 ± 1.26 (A)	11.84 ± 0.81 (B)
Soil organic carbon stock (5-20 cm depth)	n	69	67	21	25	63
	Mean	14.60 ± 1.43 (aA)	21.76 ± 1.47 (b)	18.26 ± 2.62 (ab)	16.19 ± 2.37 (A)	22.80 ± 1.49 (B)
Weighted soil organic carbon stock (0-5 cm depth)	n	74	72	21	27	66
	Mean	3.44 ± 0.53 (aA)	5.53 ± 0.54 (b)	3.93 ± 1.00 (ab)	4.05 ± 0.88 (AB)	5.62 ± 0.56 (B)
Weighted soil organic carbon stock (5-20 cm depth)	n	69	67	21	25	63
	Mean	8.79 ± 1.70	10.03 ± 0.95	8.33 ± 1.70	7.66 ± 1.55	10.40 ± 0.98
Litter carbon stock	n	98	94	26	29	91
	Mean	0.38 ± 0.39 (aA)	5.64 ± 0.40 (b)	3.02 ± 0.75 (c)	2.68 ± 0.70 (B)	5.83 ± 0.39 (C)
Weighted litter carbon stock	n	98	94	26	29	91
	Mean	0.20 ± 0.22 (aA)	2.67 ± 0.22 (b)	1.76 ± 0.42 (b)	1.44 ± 0.39 (B)	2.81 ± 0.22 (C)
Dead wood carbon stock (diameter < 5 cm)	n	98	94	26	29	91
	Mean	0.15 ± 0.13 (aA)	1.05 ± 0.13 (b)	0.67 ± 0.24 (ab)	0.46 ± 0.23 (A)	1.14 ± 0.13 (B)
Weighted dead wood carbon stock (diameter < 5 cm)	n	98	94	26	29	91
	Mean	0.09 ± 0.08 (aA)	0.52 ± 0.08 (b)	0.35 ± (0.15) (ab)	0.24 ± 0.14 (A)	0.56 ± 0.08 (B)

**Table 3.** Stocks (Mg ha<sup>-1</sup>) of the weighted soil organic carbon, litter carbon and dead wood carbon, by physiognomic-functional group.

Contenidos (Mg ha<sup>-1</sup>) del carbono orgánico del suelo ponderado, del carbono de la hojarasca y del carbono de la madera muerta, por grupo fisonómico-funcional.

Group	Comm. <i>S. divaricata</i>	Mixed woodland	Comm. <i>P. flexuosa</i>	Comm. <i>B. retama</i>	
Weighted soil organic carbon stock (0-5 cm depth)	n	2	8	8	12
	Mean	7.98 ± 4.59	7.56 ± 2.30	13.83 ± 2.30	7.09 ± 1.88
Weighted soil organic carbon stock (5-20 cm depth)	n	2	8	7	10
	Mean	20.04 ± 5.60	15.95 ± 2.80	21.28 ± 2.99	15.72 ± 2.51
Weighted litter carbon stock	n	2	8	8	12
	Mean	2.60 ± 1.57	2.99 ± 0.79	3.85 ± 0.79	2.16 ± 0.64
Weighted dead wood carbon stock (diameter < 5 cm)	n	2	8	8	12
	Mean	1.15 ± 0.45	0.38 ± 0.23	0.98 ± 0.23	0.34 ± 0.18
Dead wood carbon stock (diameter > 5 cm)	n	2	8	8	12
	Mean	2.41 ± 1.25	0.59 ± 0.62	2.20 ± 0.62	1.07 ± 0.51
Total carbon stock	n	2	8	7	10
	Mean	34.18 ± 8.53	27.48 ± 4.27	38.62 ± 4.56	25.55 ± 3.82



Deciduous plant cover showed significantly larger amounts of soil organic carbon mass (table 2) than those shown by semideciduous plant cover and the intercanopy (0-5 cm:  $F = 15.10$ ,  $P < 0.0001$ ,  $DF = 2$ ; 5-20 cm:  $F = 8.30$ ,  $P = 0.0004$ ,  $DF = 2$ ). Deciduous plant cover differed at the surface from the intercanopy though not from the semideciduous cover ( $F = 4.08$ ,  $P = 0.0186$ ;  $DF = 2$ ) in the weighted soil organic carbon stock (table 2). In the deeper layer, no significant differences were found ( $F = 1.34$ ;  $P = 0.2637$ ;  $DF = 2$ ).

When soil organic carbon stock was compared among physiognomic-functional groups at both depths (table 2), no significant differences were found in the average values per sample plot (0-5 cm:  $F = 1.96$ ,  $P = 0.1446$ ,  $DF = 3$ ; 5-20 cm:  $F = 0.87$ ;  $P = 0.4714$ ,  $DF = 3$ ). The sample plot with the largest contents of soil organic carbon stock for the 0-20 cm layer represented  $47.44 \text{ Mg ha}^{-1}$  in carbon. This plot was from a closed *P. flexuosa* woodland located in the Pipanaco saline basin (Catamarca).

The total soil organic carbon stock (0-20 cm) did not differ significantly between districts. Northern Monte District showed average values of  $25.00 \pm 2.69 \text{ Mg ha}^{-1}$  ( $n = 17$ ), while Southern Monte District had  $26.44 \pm 3.50 \text{ Mg ha}^{-1}$  ( $n = 10$ ) ( $F = 0.11$ ,  $P = 0.7464$ ). The former derived from the weighted average (0-20 cm depth) in soil organic percentages of 1.32 % under canopy and 0.66 % in the intercanopy.

The soil organic carbon stock at both depths were significantly correlated ( $C_{s\ 5-20} = 5.98 + 1.47 * C_{s\ 0-5}$ ;  $R^2 = 0.52$ ;  $P < 0.0001$ ;  $n = 157$ ), indicating that subsoil carbon stock can be estimated by topsoil carbon stock with regression equation.

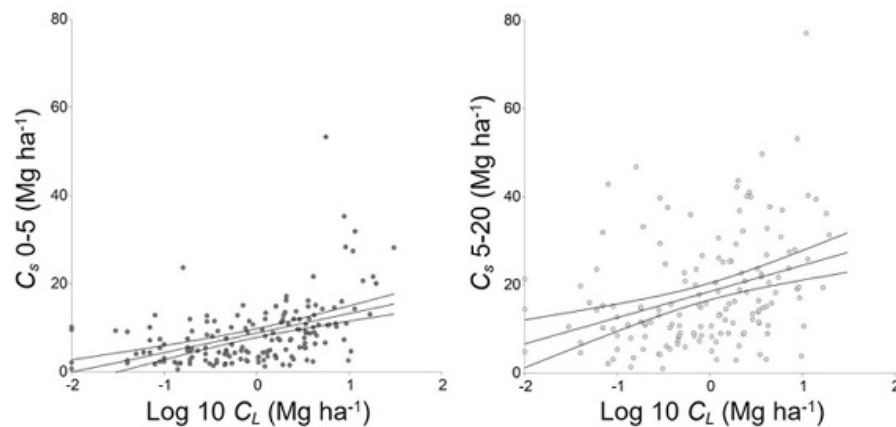
**Litter carbon stocks.** Despite the variety of materials accumulated as litter in the topsoil, litter carbon contents (% $C_L$ ) were relatively constant with 40.76 % average, 41.89 % median and 13.77 % coefficient of variation ( $n = 212$ ). No statistically significant differences were obtained between

the litter carbon contents related to the covering species ( $n = 126$ ;  $F = 0.94$ ;  $P = 0.5078$ ). No difference was found comparing plant cover ( $n = 212$ ;  $F = 0.68$ ;  $P = 0.5073$ ) or deciduousness ( $n = 212$ ;  $F = 0.94$ ;  $P = 0.3928$ ).

Litter carbon stock ( $C_L$ ) showed significant differences (table 2) among the intercanopy, under shrub canopy and tree canopy ( $F = 45.73$ ;  $P < 0.0001$ ;  $DF = 2$ ). The weighted litter carbon stock showed similar tendencies although did not differ between shrub and tree canopy treatments ( $F = 32.35$ ;  $P < 0.0001$ ;  $DF = 2$ ).

When compared between districts, no significant differences were obtained for the weighted litter stocks ( $C_{LW}$ ), discriminating by each soil cover type (IC:  $n = 98$ ;  $F = 1.74$ ;  $P = 0.1897$ . UT:  $n = 94$ ;  $F = 2.09$ ;  $P = 0.1521$ . US:  $n = 26$ ;  $F = 0.82$ ;  $P = 0.3733$ ). However, the average UT:US weighted litter stock ratio differed between Northern (1.03:1) and Southern (2.45:1) Monte Districts. The average litter stock ratio for all sites was 1.52:1.

Deciduousness had a clear and significant effect over the stocks of litter accumulated above the soil (table 2), with deciduous cover almost doubling the effect of semideciduous cover, for both unweighted and weighted values ( $C_L$ :  $F = 49.69$ ,  $P < 0.0001$ ,  $DF = 2$ ;  $C_{LW}$ :  $F = 35.87$ ,  $P < 0.0001$ ,  $DF = 2$ ). Litter carbon stock did not significantly differ between physiognomic-functional groups ( $F = 0.94$ ;  $P = 0.4344$ ;  $DF = 3$ ). Nevertheless, a tendency for higher litter carbon stock was noted for the communities of *P. flexuosa* (table 3). *Prosopis* had twice as large litterfall input as that of *Bulnesia* cover ( $3.03$  vs.  $1.50 \text{ Mg ha}^{-1}$  when values were weighted by plant cover). Litter carbon input seems to explain soil organic carbon at both depths by significant regressions. The following regression was found for topsoil organic carbon stock:  $C_{s\ 0-5} = 6.08 + 0.95 * C_L$  ( $R^2 = 0.30$ ;  $P < 0.0001$ ;  $n = 166$ ). For subsoil organic carbon stock, the following regression was found:  $C_{s\ 5-20} = 14.87 + 1.33 * C_L$  ( $R^2 = 0.15$ ;  $P = 0.0001$ ;  $n = 156$ ) (figure 4).



**Figure 4.** Soil organic carbon stocks ( $C_s$ ) at 0-5 and 5-20 cm depth and Log 10 litter carbon stock ( $C_L$ ) regression. Midline: mean regression line; lateral lines: confidence bands.

Regresión entre los contenidos de carbono orgánico del suelo ( $C_s$ ), a profundidades de 0-5 y 5-20 cm, y Log 10 de los contenidos de carbono de mantillo ( $C_L$ ). Línea media: función de regresión; líneas laterales: bandas de confianza.

*Dead wood (1 to 5 cm in diameter) carbon stocks.* Trees produced substantial amounts of small branches and twigs that were deposited on the soil, significantly different from the dead wood stocks accumulated in the intercanopy (table 2). Shrubs made a modest input of dead wood, although did not differ significantly from the intercanopy ( $C_{DW<5}$ :  $F = 12.97$ ,  $P < 0.0001$ ,  $DF = 2$ ;  $C_{DW<5W}$ :  $F = 7.34$ ,  $P = 0.0008$ ,  $DF = 2$ ).

The litter accumulated under deciduous vegetation was twice as that of semideciduous vegetation, and it was six times larger than that in the intercanopy ( $C_{DW<5}$ :  $F = 15.61$ ,  $P < 0.0001$ ,  $DF = 2$ ;  $C_{DW<5W}$ :  $F = 8.97$ ,  $P = 0.0002$ ,  $DF = 2$ ) (table 2).

Physiognomic-functional groups did not differ significantly in the diameter < 5 cm dead wood inputs (table 3). However, there was a marginal difference between mixed woodlands and communities of *B. retama*, when compared to the communities of *S. divaricata* and *P. flexuosa*, with p-values at 0.1 ( $F = 2.64$ ;  $P = 0.0912$ ;  $DF = 3$ ). The latter accumulated large amounts of dead wood under 5 cm in diameter.

*Dead wood (diameter > 5 cm) carbon stocks.* Dead wood volumes were multiplied by the following densities; *P. flexuosa*:  $0.75 \pm 0.03 \text{ Mg m}^{-3}$  ( $n = 7$ ); *S. divaricata*:  $0.66 \pm 0.02 \text{ Mg m}^{-3}$  ( $n = 9$ ); *B. retama*:  $0.80 \pm 0.02 \text{ Mg m}^{-3}$  ( $n = 9$ ); *G. decorticans*:  $0.53 \pm 0.02 \text{ Mg m}^{-3}$  ( $n = 8$ ).

Since the dead wood compartment was quantified independently from the identified treatments within each sample plot, it was only possible to compare among physiognomic-functional groups (table 3). This variable showed no statistical difference among groups ( $F = 1.45$ ;  $P = 0.2524$ ;  $DF = 3$ ). The two dead wood categories had a positive and significant relationship between each other ( $C_{DW>5} = 0.29 + 1.81 * C_{DW<5}$ ;  $R^2 = 0.47$ ;  $P < 0.0001$ ;  $n = 30$ ).

*Total dead organic carbon stocks.* The sum of the three pools (soil organic carbon, litter, and dead wood) represented significant stocks for all the four physiognomic-functional groups (table 3). *Prosopis* spp. woodlands accumulated more than  $38 \text{ Mg ha}^{-1}$  of dead organic carbon, followed by *Suaeda* spp. woodlands with almost  $35 \text{ Mg ha}^{-1}$ . Mixed woodlands, representative from Southern Monte District, showed average values around  $27 \text{ Mg ha}^{-1}$ , while *Bulnesia* spp. woodlands were the poorest with around  $25 \text{ Mg ha}^{-1}$ . No statistical differences were found among groups ( $F = 1.84$ ;  $P = 0.1683$ ;  $DF = 3$ ); nevertheless, *P. flexuosa* communities were marginally different ( $P < 0.1$ ) from *B. retama* communities, when separately compared from the rest ( $F = 4.09$ ;  $P = 0.0614$ ;  $DF = 1$ ).

## DISCUSSION

Deciduousness, *i.e.*, deciduous vs. semideciduous, has a more significant effect over soil organic carbon stocks than does soil cover, *i.e.*, tress vs. shrubs. The deciduous-

ness has an important influence in the topsoil (0-5 cm), although its effect is diluted in the subsoil (5-20 cm).

Few studies have surveyed soil organic carbon stocks in arid land regions by discriminating strata within the first five centimeters of soil depth. For example, Charley and West (1975) found for Utah rangelands important differences in the soil organic carbon stocks by comparing three depths within the top 20 cm depth. They suggest that the lack of soil mixing, litter input, and the low precipitations in arid lands, are the leading causes of carbon layering, even within the first centimeters of soil depth.

Soil organic carbon stocks per site are strongly dependent on the proportion of soil under the canopy and off the canopy. Alvarez *et al.* (2009) made the same conclusions for Ñacuñán woodlands in Southern Monte. Therefore, the elimination of plant cover should have a substantial effect on the total amounts of organic carbon accumulated in arid environments.

Tree and herbaceous plant suppression may promote encroaching of semideciduous species such as *Larrea* spp. (Villagra *et al.* 2009). Shrub encroachment reduces the amount of total litter deposited in the soil by almost 50 % (see  $C_L$  under tree canopy vs. under shrub canopy in table 2). Since litter is the primary source of soil organic carbon, a reduction in its deposition may affect the stocks of soil organic carbon. *Larrea* spp., a common shrubby species in Monte woodlands, may contribute to soil carbon stocks (as Eldridge *et al.* 2011, state for *Larrea* shrublands in the USA), though it may never reach the litter input levels of *Prosopis* spp. due to its semideciduousness and lower canopy volume.

The average ratio between the UT:US weighted litter carbon stocks found in this work (1.52:1) is similar to the annual litterfall ratio measured by Alvarez *et al.* (2009), who compared *Prosopis* spp. and *Larrea* spp. litterfall (1.4 to 1.8 in 1). By district, the average ratio for the Southern Monte (2.45:1) recorded here (and where these authors made their study) surpasses those obtained by Alvarez *et al.* (2009), while the ratio for Northern Monte (1.03:1) is quite lower. The differences between districts are mainly due to the species found in each; no communities of *B. retama*, with lower inputs of litter, were measured in Southern Monte. Differences with Alvarez *et al.* (2009) might depend on the sampling moment and the input of other species rather than *Prosopis* spp. and *Larrea* spp.

The difference between the unweighted and the weighted litter input between under tree canopy and shrub canopy suggests that trees and shrubs release different amounts of litter per surface unit ( $\text{m}^2$ ). However, ultimately this effect will be dependent on the relative cover of each type within each sample plot. Litter contents in the intercanopy are quite low due probably to slope effect, high rainfall intensity and, consequently, to runoff effect. Intercanopy areas are away from canopy influence, where cattle can move freely producing significant erosive impact. Such effect alters microtopography, forming pedes-

tals under trees and shrubs, and gullies in inter-patches. During the rainy season, water moves through gullies dragging litter away.

Dead wood is an important carbon pool. Nevertheless, the fraction of dead wood between 1 and 5 cm in diameter represents approximately one-fifth of the litter fraction, while dead wood with more than 5 cm in diameter represents almost half. Both dead wood fractions are quite variable, and their inputs depend on the climatic conditions such as rainfall or wind (Alvarez *et al.* 2009). The values obtained for dead wood in this study are slightly superior to those reported by Woodall and Liknes (2008) for drylands in the United States. Unfortunately, these authors do not detail to which species corresponds the measured dead wood, nor the sampling season.

Deciduousness is the cause that explains the large carbon stocks found in the communities of *P. flexuosa*, despite the lack of significant differences ( $P = 0.05$ ) from other plant communities. Soil organic carbon and litter are the main carbon pools in these communities. These communities are usually associated with shallow water tables, increasing the total productivity, and therefore, the amount of litter input.

In the mixed woodlands, predominantly from Southern Monte, organic carbon contents in soil and dead wood are below the average. In this group, soil organic carbon percentages are similar to those reported by Rossi and Villagra (2003) for the same district. When converted into organic matter ( $f = 0.58$ ), weighted by soil depth (0-20 cm) and discriminated by quadrant and soil cover, organic matter percentages are 2.28 % in under canopy and 1.14 % in the intercanopy. These can be compared with 2.06 % of under canopy and 0.74 % of the intercanopy, obtained by these authors.

The communities of *B. retama* have the lowest total carbon stocks, also due to deciduousness. *Bulnesia retama* is an aphyllous species that produces small amounts of litter, and this is reflected in low soil organic carbon stocks (Tapia and Martinelli 2019).

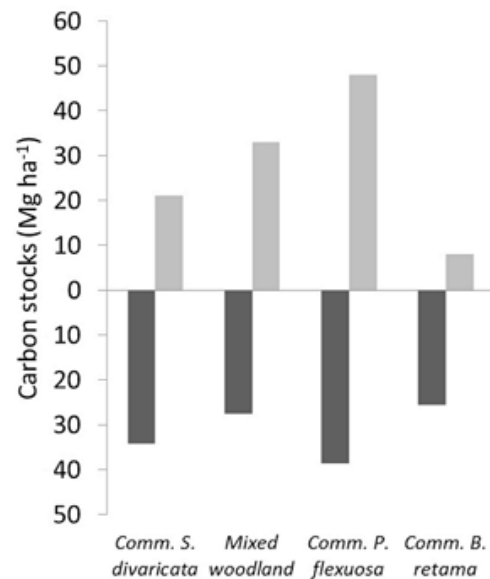
The communities of *S. divaricata* show relevant carbon stocks as soil organic carbon at 5-20 cm depth and dead wood. During the dry season in the mudflats, dust is removed from adjacent denuded areas and accumulated by deposition at the feet of the shrubs, burying the topsoil organic matter and incorporating it into the soil. Such a phenomenon is quite usual in arid lands and is the cause of the soil mixing and the inclusion of organic matter into the soil, increasing subsoil fertility (Moorhead and Reynolds 1991).

The total dead organic carbon stocks in these four communities can be related to the above-ground biomass contents measured by Iglesias *et al.* (2012) in Telteca Reserve (figure 5). The alive/dead carbon biomass ratio for the communities of *P. flexuosa*, compared with the 48 Mg ha<sup>-1</sup> of carbon in “mature forests of *P. flexuosa*,” is 1.24. In the mixed woodlands compared with the 33 Mg ha<sup>-1</sup> carbon in “mixed forests,” it is 1.20. In the *S. divaricata* communi-

ties compared with the 21 Mg ha<sup>-1</sup> carbon in “open forests with shrubs,” it is 0.61. Finally, in *B. retama* communities compared with the 8 Mg ha<sup>-1</sup> carbon in “open shrublands,” it is 0.31. The latter relates with a reduced total plant cover, characteristic in the *B. retama* communities (Tapia and Martinelli 2019), a reduced litter production and a reduced decay of dead wood due to its high density and hardness.

In this analysis (and for all the four groups), we missed the soil organic carbon from below 20 cm of depth, which according to Jobbágy and Jackson (2000), constitute considerable stocks.

Soil organic carbon and litter stocks can be compared with other ecosystems. In semiarid Chaco, with 550 mm y<sup>-1</sup> of precipitation, Abril and Bucher (2001) report 70.5, 31.0, and 15.0 Mg ha<sup>-1</sup> of soil organic carbon (0-20 cm depth) for highly restored, moderately restored and highly degraded woodlands, respectively. Regarding litter stocks, these authors report 2.60, 2.29 and 0 Mg ha<sup>-1</sup> for the same types of woodland, respectively. The four physiognomic-functional groups can be compared with the moderately restored woodland in terms of soil organic carbon (ranging between ca. 23 and 37 Mg ha<sup>-1</sup> for 0-20 cm depth) and litter stocks (ranging between ca. 2.5 and 5 Mg ha<sup>-1</sup>, by adding litter and dead wood < 5 cm). Compared with a subtropical rainforest in Misiones (Argentina), with 1,800 mm y<sup>-1</sup>



**Figure 5.** Carbon stocks in each physiognomic-functional group. In light gray, above-ground biomass carbon contents obtained by Iglesias *et al.* (2012) for Telteca Reserve; in dark gray, dead carbon biomass (soil organic carbon, litter carbon, and dead wood carbon) obtained in this study.

Contenidos de carbono en cada grupo fisiológico-funcional. En gris claro, contenidos de carbono de la biomasa aérea obtenidos por Iglesias *et al.* (2012) para la Reserva Telteca; en gris oscuro, el carbono de la biomasa muerta (carbono orgánico del suelo, carbono del mantillo y carbono de la madera muerta) obtenido para este estudio.

of precipitation, the average soil organic carbon stock in Monte region is less than half. Piccolo *et al.* (2008) report soil organic carbon contents (at 0-15 cm depth) in a Kandihumult soil of 58.9 Mg ha<sup>-1</sup>. It can be contrasted with the 47.44 Mg ha<sup>-1</sup> obtained in a closed *P. flexuosa* woodland (at 0-20 cm depth). The reported litter stocks in a mature rainforest, also in Misiones, are of ca. 5 Mg ha<sup>-1</sup> (Vaccaro *et al.* 2003). Despite the evident ecological differences from rainforests, especially in soil organic carbon content, *P. flexuosa* woodlands have the potential for reaching slightly lesser levels of soil carbon content than that reached by rainforests.

These results partially confirm the hypothesis. The carbon contents in the intercanopy are significantly reduced compared to areas under canopy. However, trees, and especially deciduous ones, produce larger amounts of litter that affect the soil organic carbon stocks. Despite that shrubs drive the soil into reduced carbon contents compared to trees, they might be important as transitional functional types to regulate carbon stocks along successional pathways.

## CONCLUSIONS

The vegetation canopy, and consequently, the litter input within fertile patches affect soil organic carbon in the topsoil. Nevertheless, carbon inputs are intimately dependent on plant functionality, such as deciduousness or canopy volume. Therefore, shrubs (especially semideciduous such as *Larrea* spp.) have a restricted ability to enrich the soil compared to deciduous trees such as *Prosopis* spp.

Soil, litter and dead wood are important pools of carbon compared to above-ground biomass in Monte region. The communities of *P. flexuosa* are the largest carbon sinks in this region. Closed *Prosopis* spp. formations can even be compared in terms of accumulated carbon, with ecosystems from more humid regions.

Soils and dead biomass can become significant pools of carbon storage in drylands compared to above-ground biomass. This aspect should be considered in programs on reducing emissions in arid regions.

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