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Potential of native forests for the mitigation of greenhouse gases in Salta, Argentina

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ABSTRACT

Carbon stocks were assessed in three archetypal forest ecosystems in the province of Salta, Argentina, namely Yungas, Chaco, and shrublands located around Chaco. Over a total area of about 7000 m², detailed measurements of woody biomass were conducted using structural information such as diameter at breast height (dbh), total height, and stem height. At the same time, the wet weight of herbaceous, shrubs, and litter was registered within that area. Soil samples were also collected to determine parameters such as bulk density and organic carbon. The above-ground tree biomass (AGB) was quantified by two non-destructive methods. This biomass was expressed from each reservoir studied in t.ha⁻¹ and the carbon content was then calculated using a factor of 0.5. Carbon stocks in the ecosystems studied were 162, 92, and 48 tC.ha⁻¹ for Yungas, Chaco, and shrublands, respectively. Our results show that carbon is concentrated in the soil or as AGB. The latter is the most important reservoir in Yungas, while the soil plays this role in the other two, drier environments. In the province of Salta, native forests play a significant role in the mitigation of greenhouse gases. Our results reveal the magnitude of carbon stocks in some characteristic regional native forests, and estimate their carbon sequestration potential. These results could be useful to inform policy makers in charge of negotiations related to conservation and sustainable management of native forests, and be a relevant input for the formulation of more comprehensive land use planning processes in the region.

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1. Introduction

World emissions of human-related greenhouse gases (GHG) increased 70% between 1970 and 2004 [1]. Rising GHG in the atmosphere are very likely causing a global climate change, as evidenced by increasing world average ambient and ocean temperatures, changes in precipitation, widespread melting of glaciers, and mounting ocean levels [2–4]. According to the Intergovernmental Panel on Climate Change (IPCC), the threat

of climate change will intensify if the global temperature rises more than 2 °C (above pre-industrial levels). To avoid this drastic increase, the atmospheric concentration of CO₂, the most important of the GHG, should be kept roughly below 450 ppmv [1]. Yet some controversy still remains regarding the stabilization level of atmospheric GHG concentrations [5]. The use of fossil fuels is known to be the main source of anthropogenic global climate change. The second largest contribution to this change is deforestation and forest degradation,

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contributing to around 18% of total global GHG emissions, a larger percentage than the entire transport sector [6].

Reducing deforestation, combined with forestation and appropriate forest management measures, would prove to be effective, immediate, and low-cost strategies to avoid significant carbon emissions into the atmosphere [7–9]. The conservation of native forests has the additional advantage of eventually allowing for the preservation of a wider range of ecosystem services that depend on the structure and processes of ecosystems [10–12]. The supply of these ecosystem services can be significantly reduced in degraded forests [13] and is also low in simpler ecosystems like forest plantations [14–17].

Indigenous people and small farmers who live in native forests could be incorporated into a management system combining carbon sequestration with energy production without jeopardizing their cultural integrity and livelihood [18–20]. Climate policies could be an opportunity to reduce GHG while, at the same time, tackling pressing problems such as the loss of biodiversity, spreading desertification, and poverty issues [21,22]. Many analysts fear such an approach will deflect attention away from the root cause of climate change, that is, GHG emissions from fossil fuel combustion in developed countries [23]. On the other hand, some tropical countries are also wary of attempts to internationalize part of their territories [21]. Finding strategies aimed at a more sustainable management of forest resources should thus take into account the multiplicity of possible uses for these resources. A delicate balance must be struck between potential carbon savings, local development, and the protection of biodiversity [24].

The quantification of carbon emissions and removals from land use changes and forestry activities is known to be complex [25]. The wide range of existing estimates of global carbon emissions from the forest sector reflects the difficulties in obtaining accurate information on this issue. Detailed studies are therefore necessary to improve the reliability of current emission estimations of the forest sector at country level. Accurate information in this respect will help standardize units, reduce uncertainties, and contribute to a more efficient strategy to limit global GHG emissions [24]. This information is also necessary to improve our understanding of forest biomass carbon stocks and describe patterns of land use change and fire regimes [26].

Argentina currently experiences the highest deforestation rate outside the tropics [27], and this loss of native forests has reached critical levels in recent years [28]. Moreover, information on the mitigation potential of native forests in Argentina is scarce. Studies are usually oriented to assess or quantify the biomass of single species [29,30]. Recent estimates indicate that deforestation represents a significant source of carbon at country level [31]. Two of the main native forest formations in Argentina are the regions called *Chaco* and *Yungas* [32]. Combined, they represent roughly 81% of all national remaining native forests [33]. In recent years, the rate of land-cover and land use change in these two regions has been the highest in the country [34]. These ecosystems are also subject to an intensive process of degradation [28]. Uncontrolled clearings for agriculture, timber overexploitation, and extensive cattle ranching are the main causes of these

combined processes. Regional surveys have shown, for instance, that more than a quarter million hectares have been deforested in the Chaco region alone in the seven years from 1992 to 1999 at an annual rate of about 5% [35]. In the lowest sections of Yungas, an area with fertile soil and favourable climatic conditions locally known as “*Selva Pedemontana*”, the rapid progress in agriculture has recently caused this area to be considered an endangered ecosystem [36]. The rate of deforestation in the province of Salta, North-West of Argentina, having 23% of the total surface of native forests in the country, is around three times as high as the world average [37]. Yungas and Chaco are both in the province of Salta [28].

In this paper we have characterized forest carbon stocks in three of the main native forest ecosystems in the province of Salta. This work is part of an ongoing project aimed at improving the estimates of the mitigation potential of these forests and contributing to a nationwide effort to create a database on the subject.

2. Materials and methods

2.1. Study area

Work was carried out in the municipality of Coronel Moldes, 60 km south of the provincial capital city of Salta. Coronel Moldes covers an area of 84,000 ha and represents 17% of a 144 km long and 52 km wide valley (Valle de Lerma). Mean altitude in Coronel Moldes is around 1,100 m.a.s.l. [38]. Climate in the region can be defined as subtropical with a dry season, and has been included within the zone of tropical climates, as an intermediate category between humid and dry climates [39]. Mean annual temperature is 17.5 °C, with maximum and minimum average temperatures of 25.3 °C and 10.7 °C, respectively [40]. Population is around 4,000 inhabitants, with more than 40% in rural areas. Population density is 5 inh.km⁻². Approximately 40% of households have unsatisfied basic needs [41]. Tobacco production is the region's main economic activity. Further activities include extensive cattle ranching, the production of crops such as beans and chilli peppers, and small scale horticulture.

2.2. Study design

No references were found regarding the characteristics of native forests in Coronel Moldes. The main natural ecosystems in the area (Chaco, Yungas, and a third one we called “shrublands”) were first detected, classified, and measured using satellite images (Landsat 5). This information was later checked and verified with Geographical Positioning System (GPS) devices during a number of specific field trips permitting first-hand observation of the current state of these ecosystems. Most representative species in the area were identified either on site or by samples collected for further analysis in the lab. A photographic database was also created during the trips.

2.2.1. Sampling design

Data were collected following a stratified random sampling design. Forests were divided into non-overlapping subpopulations or strata, according to the type of vegetation. The

criterion used to determine sample size for each stratum was an estimation of AGB of trees with a diameter at breast height (dbh) ≥ 10 cm during a pre-sampling (90% probability, 20% mean standard error). The experimental design used was nested plots. Main plots had a total area of 100 m² and were distributed as follows: 26 plots in Chaco, 23 in Yungas, and 20 in shrublands.

2.2.2. Data collection

Carbon represents about 50% of the total oven-dried biomass present in forests [42]. Estimation of carbon pools in forests necessarily involves studying the different strata of biomass present in them. In this work, the following carbon pools and variables were measured:

- a) Above-ground tree biomass (AGB). AGB refers to the total amount of above-ground living organic matter in trees and shrubs (≥ 1 cm dbh and height ≥ 50 cm) expressed as oven-dried tons per hectare. Stem height (from ground level up to first main branch), total height (from ground level up to crown point), and dbh were measured in all trees with dbh ≥ 10 cm (AGB₁₀) in 100 m² plots. When $1 \leq \text{dbh} \leq 10$ cm and height ≥ 50 cm (AGB₀), trees were measured in 50 m² plots. In multiple-stemmed trees, only the longest stem was measured. If neither shoot was dominant, an average of similar shoots was calculated. The basal diameter was registered only when the stem was shorter than the dbh. Standing dead trees with dbh ≥ 1 cm, and fallen trees with dbh ≥ 10 cm were measured in the same way as living trees. However, a correction factor of 0.8 was applied to the biomass values obtained [43].
- b) Lignified understory vegetation (LUV). All shrubs shorter than 50 cm were collected in 5 m² plots within the corners of the main 100 m² plots.
- c) Herbaceous understory vegetation (HUV). This fraction was entirely removed in two 1 m² plots. These plots were located in opposite corners within the 100 m² plots used to measure AGB₁₀.
- d) Litter (LI). Organic debris on the soil surface, including freshly fallen parts of plants, decomposing organic matter, and dead wood with a diameter no greater than 10 cm were collected in the same plots used for HUV.
- e) Below-ground biomass (BGB) (tree roots). Due to the difficulties involved in the measurement of BGB, this fraction was estimated indirectly as a proportion of AGB₁₀ for Chaco and Yungas. For shrublands, most of the trees fell below 10 cm in dbh. Therefore, the calculation of BGB for this ecosystem was based on both the AGB₀ and AGB₁₀ fractions.
- f) Soil. Bulk density and percentage of organic carbon were determined in soil samples collected at a depth of 30 cm [44]. Vegetation and litter were removed from the soil surface prior to sampling. Bulk density was determined in two samples per plot using the cylinder method [45]. Results from these samples were averaged. The percentage of organic carbon was measured following the method described in Walkley and Black [46]. This measurement being performed on a composite sample built from four samples taken at identical distances within a linear transect along the longest axis of the 100 m² plots (dimensions of these plots were 5 m \times 20 m).

Wet weight was recorded on site for LUV, HUV and LI fractions. Dry weight was determined in the lab (registered after drying in an oven at 80 °C until constant weight). The equation introduced by Kurz and co-workers [47] for hard woods was used to estimate the BGB fraction in the Chaco region. In Yungas and shrublands, equations for soft woods were applied instead. The AGB fraction, also called 'biomass density' when expressed as tons of oven-dried weight per ha [42], is the main source of total biomass in a forest ecosystem. Its relevance as a GHG mitigation option is therefore crucial [7,48]. This fraction was thoroughly assessed using two non-destructive methodologies [42]: i) biomass expansion factor (BEF); and ii) allometric equations (AE). A description of these methods is provided in the next section.

2.2.3. Estimation of AGB

2.2.3.1. *Method 1 (the BEF)*. For the BEF method, volume data from the Forest Inventory of the Argentinean north-west were used [49]. For some species, no data were available. In those cases, volumes of species from the same environment were utilized. Volume data for dbh < 10 cm were extrapolated from existing tables. AGB₀ and AGB₁₀ were calculated with equation (1).

$$\text{AGB} = \text{VOB} \times \text{WD} \times \text{BEF} \quad (1)$$

Where

AGB (t.ha⁻¹) = above-ground tree biomass.

VOB (m³.ha⁻¹) = volume of stem wood (from ground level up to first main branch).

WD (t.m⁻³) = volume-weighted average wood density (oven-dried biomass per green volume).

BEF (–) = biomass expansion factor.

VOB was calculated using data of dbh and stem height per plot. Biomass in the plots (BV, in t.ha⁻¹) was estimated by multiplying the average VOB by WD. Data of WD were obtained from the database compiled by INTI – CITEMA [50]. Where no data were available or species could not be identified, the WD used for the calculations were 0.766, 0.745, and 0.695 t.m⁻³ for Chaco, Yungas, and shrublands, respectively. When BV values < 190 t.ha⁻¹, the BEF was calculated with equation (2) [42]. BEF reaches constant values between 1.7 and 2.0 in primary tropical forests around the world [51].

$$\text{BEF} = \exp^{3.213 - 0.506 \times \ln \text{BV}} \quad (2)$$

2.2.3.2. *Method 2 (allometric equations)*. For comparison purposes, AGB was also calculated using allometric equations (AE). Two equations with a different number of variables, proposed in the literature for similar ecosystems, were selected for each ecosystem under study (Table 1). The purpose of these calculations was to assess to what extent the extra work involved in estimating a larger number of variables was justified in terms of the accuracy or precision of the final outcome.

The equations of Table 1 have been derived for specific ranges of dbh. In our case, the upper limits of those ranges were never exceeded. The lower limits set for two of the six equations used could not always be respected. This situation was considered acceptable as long as the thinnest dbh fractions represented only a small proportion of the total biomass in the

Table 1 – Allometric equations used to estimate biomass density (AGB₀ and AGB₁₀). D = dbh (cm); ρ and S = wood density (g cm⁻³); H = total height (m); BA = basal area (cm²); Y = tree biomass (kg); BF = biomass of main stem (kg).

Ecosystem	Equation	Number	Reference
Yungas	$Y = 34.4703 - 8.0671(D) + 0.6589(D^2)$	(3)	[51]
	$Y = \exp\{-2.4090 + 0.9522 \times \ln(D^2 \times H \times S)\}$	(4)	[51]
Chaco	$Y = \exp\{-1.996 + 2.32 \times \ln(D)\}$	(5)	[42]
	$Y = 0.112 \times (\rho \times D^2 \times H)^{0.916}$	(6)	[54]
Shrublands	$Y = 10\{-0.535 + 0.9996(\log_{10}BA)\}$	(7)	[55]
	$BF = 0.1368 (D^2 \times H)^{0.7559}$	(8)	[53]

ecosystems studied. For shrublands, AGB was obtained as the BF value (calculated with equation (8) in Table 1) plus 60%, to account for the biomass contained in branches. This calculation assumes that the biomass of the shaft represents about 40% of the total biomass, as indicated in the literature [52,53].

2.2.4. Carbon stock

For both methods, the carbon content was calculated by multiplying the results obtained for AGB by a factor of 0.5, as recommended when no specific data are available [1,42]. All other studied fractions of biomass (LUV, HUV, LI, and BGB) were converted into carbon pool by applying the same factor. As an exception, total organic carbon in the soil was calculated with equation (9) [44].

$$\text{SOC} = \%OC \times BD \times D \quad (9)$$

Where:

- SOC = soil organic carbon (t.ha⁻¹);
- OC = concentration of organic carbon in the soil (%);
- BD = bulk density of soil (g. cm⁻³); and
- D = depth of soil (cm).

2.3. Data analysis

Data gathered for AGB₀ and AGB₁₀, having used both BEF and AE methods, did not follow a normal distribution (when analysed using the Kolmogorov–Smirnov test) and presented non-homogeneous variances (determined by the Levene test). Therefore, the Kruskal–Wallis non-parametric statistical test was applied to analyse and compare these data. When significant differences were detected between series of data, the Mann–Whitney pair-comparison test was applied. Two-tailed tests at a significance level of 0.05 were used [56]. Carbon pools were calculated as the average between AGB estimations that demonstrated no significant differences. In the case of Yungas, significant differences were detected between all of the estimations of AGB₀. For this case, an average of the three estimations obtained was used to calculate the carbon pool.

3. Results and discussion

3.1. Current state of local forests

The three ecosystems studied are located along an East–West line, from the mountainous areas with relatively high precipitation in the West (Yungas) to the shrublands in the

easternmost part. Population density is highest in the Eastern part and decreases gradually to the West.

The lower Yungas forest (located below 1,400 m.a.s.l.) is represented by 2,600 ha in Coronel Moldes, about 25% of the total Yungas forests in this municipality. Average rainfall in this section of Yungas is 900 mm. Most common tree species found within this ecosystem were *Phyllostylon rhamnoides* (“palo amarillo”), *Anadenanthera colubrina* (“cebil”), *Tipuana tipu* (“tipa”), *Enterolobium contortisiliquum* (“pacará”). These species were detected above 1,200 m.a.s.l. in the study area although they are usually found below 900 m.a.s.l. [32]. Individuals of *Schinopsis haenkeana* (“horco-quebracho”) and *Fagara coco* (“coco”) were also detected, which are typical traits in some regions of Chaco (“Chaco Serrano”) [32]. *Solanum riparium* was also abundant in this area, a species normally dispersed by wild animals or cattle. The appearance of typically Chaco species in sections of Yungas forest is probably a sign of human intervention in this region [36,57].

Chaco, with 40,000 ha, is the largest ecosystem in Coronel Moldes. Average rainfall is around 500 mm, concentrated between October and March [32]. In the study area, the Chaco ecosystem has lost some of its original characteristics, as described in literature [58–60]. In fact, species like *Schinopsis quebracho-colorado* and *Aspidosperma quebracho-blanco* (locally known as “quebrachos”) are only found sporadically, after decades of targeted logging. Our trips to the region led us to conclude that the forest structure has been reduced to only two strata: (a) a higher stratum dominated by *Prosopis nigra* (“algarrobo”), *Zizyphus mistol* (“mistol”), *Cercidium australe* (“brea”), *Caesalpinia paraguayensis* (“guayacán”), and *Geoffroea decorticans* (“chañar”); and (b) a dense lower stratum, mainly composed of shrubs from the genus *Acacia* and *Celtis*.

The ecosystem we defined as “shrublands” occupies an area of around 6,900 ha. This area is covered by shrubs (generally below 5 m) and isolated trees, with patches of native grass. *Acacia* species are widespread. Shrublands can be local original ecosystems, as indicated by Cabrera [32], or may have originated in past clearings of native forests for agricultural purposes, forest fallows, or cataclysmic events like floods or forest fires, as discussed in Cozzo [61].

3.2. Biomass density estimates for each forest

AGB₁₀ estimations decrease from Yungas to shrublands, with intermediate values in Chaco, for both methods used (Table 2). Low water availability and high human presence in shrublands are probably the main reasons for this trend [59,62].

The BEF method generally provides higher values than the AE method for all ecosystems studied. This was especially clear for AGB₀. Only for AGB₁₀ in Yungas, differences found between the methods were not statistically significant (using equation (4)). In Chaco, the estimation obtained with the BEF method is almost twice that calculated with AE for AGB₁₀, and almost four times higher than the estimation for AGB₀. The BEF method, known to be less precise, is accepted to make estimations over large areas [51,63], as it allows the conversion of extensive forest volume data to biomass estimates [62]. Extrapolations for the category under 10 cm dbh may influence the estimates. In our case, this influence was considered negligible for Yungas because the fraction under 10 cm dbh is relatively small. In the case of shrublands, the error might be bigger due to the larger presence of this fraction.

Both allometric equations (AE) used for Chaco and shrublands provided similar results, although equations with more variables have sometimes been recommended [54]. The degraded horizontal and vertical structure of these forests, with short trees (<10 m) and small diameters (only some isolated individuals reached a dbh of 30 cm), may be the reason why results are so close to one another for these two ecosystems. In fact, average height in Chaco and shrublands was 6.7 and 4.8 m, respectively (for dbh ≥ 10 cm). In shrublands, 88% of the trees registered showed dbh < 10 cm while 70% was ≤ 5 cm, with an average height of 2.9 m (in the category of AGB₀). In Yungas, average height was 11 m and average dbh was 17.6 cm, both higher than those for Chaco and shrublands, although still lower than figures cited for pristine Yungas ecosystem [32,64]. For the latter environment (Yungas), the difference between the two allometric equations used was increasing as the trees reached greater heights. Biomass increases sharply in equations including height especially when this variable is higher than 10 m.

Estimations made for tropical humid forests around the world range from 150 to 192 t.ha⁻¹ for closed, undisturbed forests [51], and around 50 t.ha⁻¹ for open forests [65]. The total amount of AGB in jungle-like environments is probably the result of a combination of factors such as rainfall [66], type of soils and nutrients content [67], topography, elevation, and their interaction [68], type of forest (primary or secondary forests) [13,66], forest structure [17,24], type of landscape or other aspects associated with regional scale [69,70], and degree of disturbance [62,71,72], among others. Only two references could be found that report higher values for Argentinean Yungas, one with the BEF method and one using AE [31,73]. It can be safely assumed that these differences are mainly due to the different scale of the studies, since the

works cited considered all the altitudinal belts of the Yungas and the whole surface of this ecosystem in the country. Moreover, the structure of the forest in the Yungas area included in this study was clearly disturbed by humans and livestock. Numerous recent and decomposing stumps were found and there were unambiguous signs of wandering animals and persons.

In environments similar to Chaco, discrepancies between these results and estimations made in similar environments in other forests of the world might be due to structural differences, as suggested by Martínez-Yrizar and others in their studies of tropical deciduous forests in Mexico [55]. Different altitude [74], latitude [75], and humidity gradients [59] in our case might also be responsible for the discrepancies. The level of degradation exerted by human activity in this environment is high, as noted in previous studies [35,59]. Bonino found that forest harvest and deforestation in Chaco produced a drastic reduction in biomass stock in trees, decreasing from 50.9 t.ha⁻¹ in the primary forest to 10.2 t.ha⁻¹ in the secondary forest [59]. Height has been an important adjustment variable in our case, reducing previous estimations made for AGB₁₀ in Chaco by using AE [31]. The AE method appears to be more able to detect local variations, whereas the BEF method could not detect such differences, giving similar results to previous national estimations made with this method [73]. The lower sensitivity of the BEF method for Chaco could be due to the fact that this forest is not as closed as the forests in which the method was originally developed [42].

There are only a few studies referring to ecosystems such as our shrublands. In Mediterranean shrub communities, Navarro and Blanco [76] reported estimations of AGB fluctuating around 4.5 to 17 t.ha⁻¹, depending on the type of shrubland. These authors mention that shrub biomass density varies considerably according to climatic, edaphic, and topographic differences, and also due to the history of land use and the types of human disturbance. In Montado (Portugal), Castro and Freitas [77] studied shrublands originating from natural forests following the removal of trees by human activity such as clearing, burning, and grazing. The increase in AGB after abandonment was strongly related to the increase in shrub cover. Biomass yields ranging from 1.95 t.ha⁻¹ in herbaceous-dominated communities to a maximum of 11.6 t.ha⁻¹ in advanced succession (shrub-dominated communities) were found. In Argentina, AGB values around 2.75 t.ha⁻¹ were reported for shrubby grassland, defined as a community composed of a low-density layer of saplings of trees and shrubs and characterized by the absence of a tree cover [59]. The very definition of “shrubland”

Table 2 – Biomass density in t.ha⁻¹ (average ± mean standard error) estimated by two non-destructive methods, the Biomass Expansion Factor (BEF) and Allometric Equations (AE). Means followed by different letters (a, b, and c) within the same row indicate significant differences ($P < 0.05$).

Ecosystem	n	BEF		AE (number 3, 5, and 7)		AE (number 4, 6, and 8)	
		AGB ₀	AGB ₁₀	AGB ₀	AGB ₁₀	AGB ₀	AGB ₁₀
Yungas	23	27.6a ± 3.1	147.5a ± 10.7	14.5b ± 1.5	82.2b ± 8.8	6.2c ± 0.8	130.1a ± 17.0
Chaco	26	16.6a ± 1.7	104.8a ± 6.7	4.5b ± 0.5	58.6b ± 5.9	4.0b ± 0.4	54.5b ± 6.1
Shrublands	20	23.3a ± 2.8	31.9a ± 8.1	9.5b ± 1.9	8.4b ± 2.4	10.4b ± 2.3	7.7b ± 2.4

is vague and dominant species in each shrubland are different too. Therefore, differences in biomass estimations should not come as a surprise, as indicated by Cozzo [61]. More studies are necessary for these types of highly-variable, context-dependent environments to assess their potential as carbon sinks, especially bearing in mind that these ecosystems sometimes present a close correlation with the level of SOC, as some studies have already shown [78,79].

3.3. Carbon stock for the different ecosystems

Fig. 1 shows the total carbon stock estimated for the three ecosystems, with all pools considered. Based on these results, it was calculated that about 16 Mt of CO₂ have been sequestered from the atmosphere in 50,000 ha. Considering that an average Argentinean citizen emits almost 6 tCO₂·y⁻¹ [80], the values obtained in our studies are roughly equivalent to the emissions of 3 million inhabitants in one year or the emissions of more than three times the entire population of the province of Salta [41].

Fractions AGB₁₀ and SOC are the largest contributors in all cases (Figs. 1 and 2). In Yungas, the most humid ecosystem of the three studied, above-ground tree biomass (both AGB₀ and AGB₁₀) represent 45% of the total carbon fixed, while the soil contributes 36.5%. In Chaco and shrublands, on the other hand, the carbon retained in the soil is 1.7 and 3.7 times higher than in above-ground tree biomass. In shrublands, the contribution of AGB₀ is higher than that of AGB₁₀, a situation which has not been observed in the other ecosystems studied.

The soil is an important carbon reservoir, becoming the most relevant fraction in drier environments. However, when comparing the absolute values of SOC between the three environments (Table 3), the soil shows an important relationship with the vegetation found above the ground. The SOC involves 69.4% of the total carbon stock of the shrublands although, when expressed in absolute terms, represents only 65% and 52% of the SOC in Chaco and Yungas, respectively. The maintenance of a vegetation cover is therefore important as it will eventually be incorporated into the soil improving its fertility, porosity, infiltration rate, water retention capacity, and resistance to erosion, as noted in a number of studies [17,59,67,81].

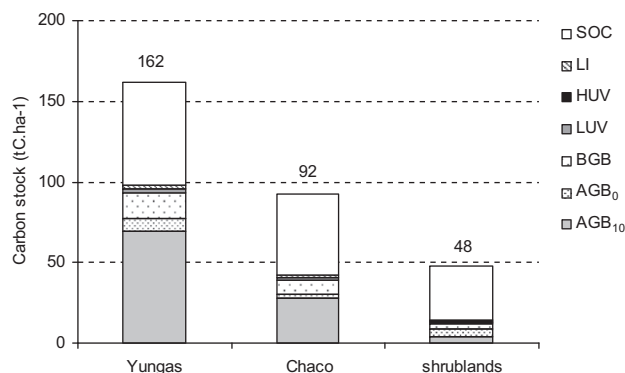


Fig. 1 – Total carbon stocks (tC·ha⁻¹) estimated for the three ecosystems studied.

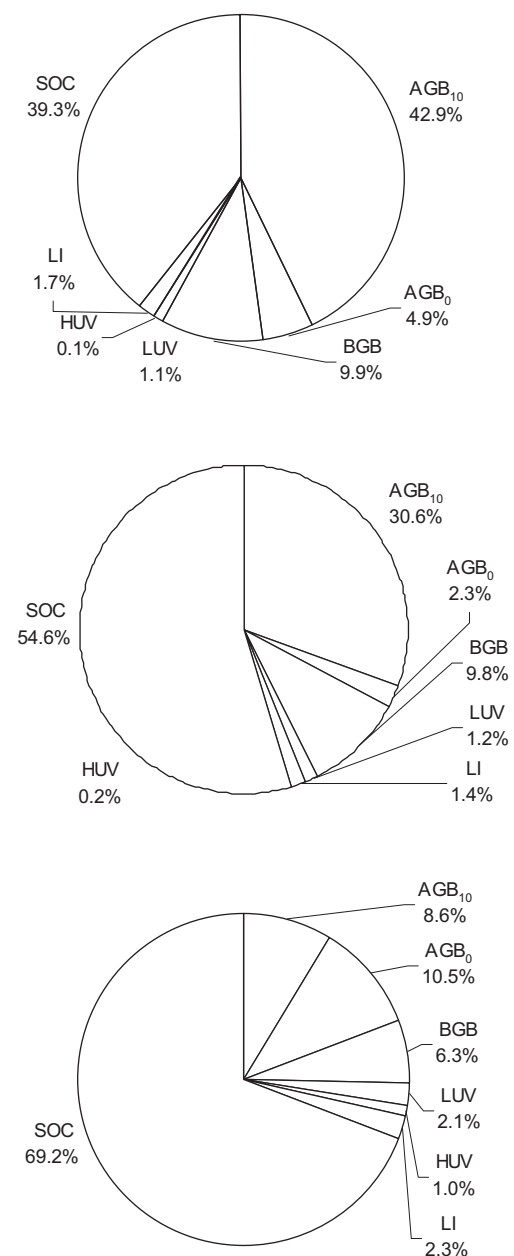


Fig. 2 – Proportion of carbon found in each reservoir for Yungas (top), Chaco (centre), and shrublands (bottom).

The remaining reservoirs (BGB, LUV, HUV, and LI) together represent only 19, 16, and 12% of the total carbon stock in Yungas, Chaco and shrublands, respectively. In all cases, the BGB fraction made the greatest contribution.

3.4. Forestland use planning and climate change mitigation

The forest formations studied in Coronel Moldes are represented in the province of Salta with 5.6 million ha of Chaco, 2.3 million hectares of Yungas and about 900,000 ha of other wooded land [33]. Assuming these areas have identical characteristics as the forests studied, it can be estimated that

Table 3 – Carbon stored (average \pm standard deviation) in the main carbon pools (in tC.ha⁻¹) for all ecosystems studied. See description of acronyms in the text.

Ecosystem	n	AGB ₁₀	AGB ₀	BGB	LUV	HUV	LI	SOC
Yungas	23	69.4 \pm 34.0	8.0 \pm 6.5	16.1 \pm 7.5	1.2 \pm 0.5	0.1 \pm 0.1	2.8 \pm 1.4	63.0 \pm 34.7
Chaco	26	28.2 \pm 12.8	2.1 \pm 1.2	9.0 \pm 2.8	1.8 \pm 0.9	0.2 \pm 0.3	2.1 \pm 1.0	50.4 \pm 22.9
Shrublands	20	4.0 \pm 4.6	5.0 \pm 4.0	3.0 \pm 1.2	0.4 \pm 0.2	0.5 \pm 0.4	1.0 \pm 0.5	32.8 \pm 11.3

about 3 billion tCO₂ are sequestered by these forests in the province. This estimation should be confirmed with measurements in other parts of the province where these forests are also present. These ecosystems are undergoing rapid deforestation [28]. Our results suggest that forest degradation is not only limited to shrublands, but that it is also detectable in Yungas and Chaco. Economic activities such as agriculture and logging which take place in these ecosystems are arguably not respecting their carrying capacity. Local institutions do not seem to be capable of stopping, controlling, or regulating these activities. A recent land use planning process carried out in the province of Salta has been criticized by environmentalists and scientists alike for its alleged ambiguity and softness on loggers and big agricultural producers. Indigenous peoples and small farmers have even made a case before the country's Supreme Court of Justice in order to stop logging and agricultural clearings until a final decision is reached on the ownership of the land. The Supreme Court has preliminarily ruled to stop all deforestation activities in four departments of the Province, but the final decision is still pending. A detailed description of this case is out of the scope of this paper. Whether entering into a market-based system like the one promoted by the Kyoto Protocol will be part of the solution to the problem of deforestation and conservation of local native forests remains to be seen. Decisions are highly political and many times the relevant decision-makers are thousands of kilometres away. No decisions affecting the future of these forests should be taken until agreements on this issue are reached or until judiciary processes are properly finished. Competing claims on the ownership of the forest land, the products of the forests, and the provision of ecosystem services must be taken into consideration in a comprehensive forest management [12,24].

Different strategies could be used to incorporate the potential of native forests for the mitigation of GHG into land use planning initiatives. In general terms, native forests can be managed to maintain or enhance existing carbon stocks in forests or to replace fossil fuels with the use of biomass as energy source [7,9,48]. GHG mitigation objectives can be combined with other local economic development objectives and the conservation of biodiversity [18,21].

AGB would yield, in shrublands alone, about 38,000 GJ.ha⁻¹.y⁻¹, assuming a growth of about 0.54 t.ha⁻¹.y⁻¹ and a harvest efficiency of 70%. The mitigation potential would depend on which type of fossil fuel gets replaced in each case [18]. It can be calculated that, on average, about 3 kg of biomass can replace 1 L of petrol. Table 4 presents some rough calculations that may illustrate the potential of using the biomass generated in the ecosystems studied as energy source. The bioenergy potential was calculated according to FAO [82], where annual productivity, a poorly studied variable

for the country's native forests, was estimated as a percentage of the stock of above-ground tree biomass in each ecosystem (considering both AGB₀ and AGB₁₀). A 2% annual productivity rate for Yungas and a 3% annual productivity rate for Chaco and shrublands were considered. This means an annual growth of 3.1, 1.8 and 0.5 t.ha⁻¹.y⁻¹, respectively. The potential of biomass available for energy purposes was estimated at 70 and 80% of the annual growth. Most of the annual harvest should be done in the biomass fraction with a dbh \geq 10 cm (AGB₁₀), except for shrublands (Table 4). For Coronel Moldes, any of the factors used (70 and 80%) would mean a bioenergy potential of about 866–990 TJ (Terajoule: 10¹²J) per year or around 21 to 24 thousand tons of oil equivalent (toe; 1 toe is approximately 42 GJ) of fossil fuels substituted, according to the replacement fuel (e.g. natural gas or diesel).

The use of all available bioenergy present in the studied forests could mitigate the emissions of 8,000 to 12,000 inhabitants, which represents double and triple the current municipal population. However, it is important to note that not all potential resources are accessible and availability varies spatially, thereby significantly reducing the available stock in many places. Any proposed use of biomass for energy purposes should be studied in detail depending on physical, economic, social, cultural, technological, and legal constraints.

The forests of Chaco and Yungas could also be recovered and enriched, and these practices could maintain and even increase current carbon stocks [18,19,83]. While carbon sequestration capacity decreases as it reaches the carbon carrying capacity of a forest ecosystem [26] or *climax*, if these forests are managed properly, their ability to sequester carbon may be maintained over time [83] and will also have a positive impact on biodiversity, local economy, and other social aspects [84,85]. The state of degradation found in the forests studied suggests that the carbon sequestration capacity of these forests is likely to be greater than estimated.

Table 4 – Biomass and bioenergy potentials for each ecosystem, according to different usage factors. Annual productivity considered (as a percentage of the stock of above-ground tree biomass) was 2% for Yungas and 3% for Chaco and shrublands.

Ecosystem	AGB ₁₀ used (%)	Biomass		Bioenergy	
		potential (t.y ⁻¹)		potential (GJ. y ⁻¹)	
		Usage factors			
		70%	80%	70%	80%
Yungas	89.6	5.6	6.4	82.3	94.1
Chaco	93.2	51	58.2	745.5	852.1
Shrublands	44.3	2.6	3	38.2	43.6

4. Conclusions

Carbon stocks in the ecosystems studied were 162, 92, and 48 tC.ha⁻¹ for Yungas, Chaco, and shrublands, respectively. The main carbon reservoirs in all three ecosystems are AGB and soil. AGB is the most important reservoir in Yungas, while soil plays this fundamental role in the other two, drier environments.

Overall, indirect methods appear to be effective choices for estimating above-ground tree biomass. Yet, when it was possible to collect local field data, the AE method seemed more accurate. In Yungas, there were differences between both allometric equations used, and this paper therefore advises incorporating height and wood density data when using them to improve their accuracy.

This study suggests that carbon stocks in native forests, particularly in Chaco and Yungas, could be restored, maintained, or even increased through the application of simple silvicultural practices. This should be relevant to local and national decision makers in charge of negotiations concerning the conservation, sustainable management of forests, and enhancement of forest carbon stocks.

Native forests in the province have a high potential for the mitigation of GHG, since the use of available biomass might replace fossil fuels and concomitantly reduce CO₂ emissions. The carbon sequestration potential in the ecosystems studied suggests that it could be part of a broader strategy aiming to set up more comprehensive and sustainable land use planning in the region.

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