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RESEARCH NOTE

How much carbon is stored in the terrestrial ecosystems of the Chilean Patagonia?

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Abstract
We estimated the amount of carbon (C) stored in terrestrial ecosystems of the Chilean Patagonia and the proportion within protected areas. We used existing public databases that provide information on C stocks in biomass and soils. Data were analysed by ecosystem and forest type in the case of native forests. Our results show that some ecosystems have been more extensively studied both for their stocks in biomass and soils (e.g. forests) compared with others (e.g. shrublands). Forests and peatlands store the largest amount of C because of their large stocks per hectare and the large area they cover. The total amount of C stored per unit area varies from 261.7 to 432.8 Mg C ha^{-1}, depending on the published value used for soil organic C stocks in peatlands, highlighting the need to have more precise estimates of the C stored in this and other ecosystems. The mean stock in national parks (508 Mg C ha^{-1}) is almost twice the amount stored in undisturbed forests in the Amazon. State and private protected areas contain 58.9% and 2.1% of the C stock, respectively, playing a key role in protecting ecosystems in this once pristine area.

KEYWORDS
carbon density, carbon sequestration, South America, storage, temperate rainforests

INTRODUCTION

The carbon (C) stored in biomass and soils can be lost not only as carbon dioxide or methane naturally (FAO, 2017) but also because of human perturbations such as land use change, particularly deforestation (Kindermann et al., 2008), peatland drainage (Konecny et al., 2016) and fires (Perez-Quezada, Urrutia, et al., 2021). Quantifying the C stored in different ecosystems provides relevant information for developing adaptation and mitigation strategies to address climate change, for example, by setting the baselines to estimate the effects of ecosystem protection or restoration projects.

The Chilean Patagonia is in a relatively pristine state compared with other areas in the country and around the world, and hosts the largest area and latitudinal extent of temperate forests in the Southern Hemisphere (Armesto et al., 2009). Perturbations have modified the landscape in a few areas, mainly through human-caused fires that have converted forests into steppe shrublands and the introduction of grazing and invasive species such as the North American beaver (Jaksic & Fariña, 2015). Studying the C stocks in this area is particularly important because temperate forests can store more C in biomass compared to tropical and boreal forests (Keith et al., 2009) and because exploitative interventions are known to decrease soil organic C stocks in *Nothofagus* forests (Klein et al., 2008). Therefore, the objectives of this study are as follows: (1) to estimate the amount of C stored in biomass and soils in the terrestrial ecosystems of the Chilean Patagonia, and (2) to estimate how much of the total C is stored in protected areas.

MATERIALS AND METHODS

Study area

The study area covered part of the Los Lagos region (Chiloé and Palena provinces) and the Aysén and Magallanes regions (41°–56° S). Climate in this area includes an oceanic rainy zone (south of Los Lagos and west of the Aysén Region), a cold steppe zone (east of Aysén and Magallanes regions) and a tundra zone (west of the Magallanes Region).

The area covered by each ecosystem and native forest type, including agricultural lands and exotic pine plantations, was determined using the Vegetation Cadaster developed by the National Forest Service (CONAF, https://sit.conaf.cl) for Magallanes in 2005, Aysén in 2011 and Los Lagos in 2013.

Carbon in biomass

Carbon in biomass ($\mathrm{Mg\,C\,ha^{-1}}$) for forests was estimated from thematic maps (1-ha pixel) generated by the National Forest Inventory (NFI), led by the Chilean Forest Institute (INFOR) (Bahamondez et al., 2021) and downloaded from the Integrated System for Monitoring Native Forest Ecosystems (SIMEF) platform, generated by INFOR, CONAF and the Center for Information on Natural Resources (CIREN): https://simef.minagri.gob.cl/descargas.

These maps are based on field biomass C data.

$$\mathrm{Bc_i} = \mathrm{Sv_i} \times \mathrm{BEF} \times (1 + \mathrm{Rf}) \times \mathrm{Wd} \times \mathrm{Cf} \tag{1}$$

where Bc_i is the carbon in biomass for species i, Sv_i is stem volume ($m^3 ha^{-1}$) for species i (Gayoso et al., 2002), BEF is the aerial biomass expansion factor (1.75; IPCC, 2006), Rf is the root expansion factor (0.29, Gayoso et al., 2002), Wd is wood density (0.5 $Mg\,m^{-3}$; IPCC, 2006) and Cf is the carbon fraction of biomass (0.47; IPCC, 2006).

Sampling points in this inventory are distributed on a systematic 7 km (North–South) by 5 km (East–West) anisotropic grid. In each of the randomly selected sampling points, one conglomerate of three circular 500 m^2 concentric plots is measured (i.e. not all sampling points have been sampled yet). The inventory is performed on a 4-year cycle, where $>3\times10^6$ ha are selected to be measured annually, but the actual number of conglomerates measured depends on budget. Of the total number of conglomerates measured annually, 25% correspond to plot remeasurements.

Input data for estimating forest biomass C stock consisted of thematic stem volume maps, generated through the combination of plot data, remote sensing data and the use of machine learning techniques. As no thematic maps were available for biomass, the stem-volume maps were used, along with a generic biomass function from Gayoso et al. (2002).

For those ecosystems for which SIMEF does not estimate biomass C, we used bibliographical information available for the area, specifically for steppes (Ahumada & Faúndez, 2001), shrublands and grasslands (Perez-Quezada et al., 2022), plantations (Dube et al., 2012; 18-year-old *Pinus ponderosa* plantation with 800 trees ha^{-1}), beaches and dunes (Liliana Vásquez, unpublished data) and peatlands (Cabezas et al., 2015).

Carbon in soil

Soil organic carbon stock (SOC, Mg C ha^{-1}) was estimated for profiles available from the Chilean Soil Organic Carbon (CHLSOC) database (Pfeiffer et al., 2020), as the sum of C content in their horizons (SOC_i):

$$SOC\_i = (\text{bottom} - \text{top}) \times Bd \times OCf \times 10 \quad (2)$$

where bottom is the horizon's lower boundary (m), top is the horizon's upper boundary (m), Bd is the bulk density ($kg\,m^{-3}$) and OCf is the organic C fraction.

From the CHLSOC database, 2238 georeferenced data points were used to estimate SOC in the study area. For 1465 of these data points, the bulk density was estimated by assigning the average value of the corresponding land use. The mean SOC value for each forest and the other ecosystem types was obtained from all the corresponding profiles, according to their coordinates and the Vegetation Cadaster map.

Estimation of mean total carbon by ecosystem and the storage in protected areas

The mean total C (biomass C + SOC) was estimated for each ecosystem type. To estimate the regional total C stock, this value was multiplied by its area in the Chilean Patagonia using the 1-km pixel grid map obtained from SIMEF. To estimate how much C is stored in protected areas (PA), their polygons were overlapped with the total C map. Polygons of both State and private PAs were obtained from the National Database of Protected Areas from the Ministry of the Environment (http://areasprotegidas.mma.gob.cl/).

RESULTS AND DISCUSSION

Carbon in biomass and soils by forest type

Table 1 shows the mean C stocks in biomass and soils by forest type for the study area, while Table S1 shows the C in biomass by forest type by region. From the area covered by forests, the most abundant types are *Nothofagus pumilio* (35%), evergreen (32%) and *Nothofagus betuloides* (22%), while the other forest types covered ≤7% each. All forest types stored more C in the soil than in biomass, except for *N. pumilio*. This pattern has been reported for temperate forests and differs from tropical forests, which have a more even distribution (Watson et al., 2000).

The forest type with the highest biomass C stock was *Fitzroya cupressoides*, while the one with the lowest was *Pilgerodendron uviferum*, showing a difference between the two of only 31 Mg C ha^{-1} (Table 1). This small difference is surprising given the different forest structures and large expected size of some tree species like *Fitzroya* and *Nothofagus* sp. of the evergreen forest type. This pattern may be partly due to the impossibility to assign C stock values to different forest development stages. For example, *F. cupressoides* forests in the Andes may reach above-ground C stock values of ~15 Mg C ha^{-1} in young, ~192 Mg C ha^{-1} in mature and more than 500 Mg C ha^{-1} in old-growth forests (González et al., 2022; Urrutia-Jalabert et al., 2015). Although biomass C stocks data in forests are generated using a sampling scheme that facilitates that all forest development stages are represented, these data are broadly integrated by the National Forest Inventory (NFI) when calculating biomass from stem volume thematic maps, hampering a more precise estimate of C stocks by forest type. The observed pattern may also partly reflect the still scarce forest sampling coverage despite efforts displayed by the NFI.

The lowest SOC stock was found in *N. pumilio* forests, while the highest was observed in the *Nothofagus dombeyi–Nothofagus alpina–Laureliopsis philippiana* type, although the latter value is the result of only one soil profile, highlighting the uneven number of sampling points between forest types. The total C stock in the evergreen forest type (469.1 Mg C ha^{-1}) is lower than the value reported for a forest in northern Patagonia (993.4 Mg C ha^{-1}; Perez-Quezada, Pérez, et al., 2021), but higher than the one found in an evergreen forest in New Zealand (275.6 Mg C ha^{-1}; Hart et al., 2003).

The lack of data or uneven sampling may generate under- or overestimation of SOC, or an underestimation if the maximum soil depth was not reached by the sampling. Even though the three forest types with the highest area are also those that show the highest number of SOC samples, based on the data from Table 1 we found no relation between the forest type total area and the sampling effort (number of hectares that each sample represented). Because the soil database gathers information generated by different authors who had different objectives, we found an uneven spatial distribution of samples in the study area, showing a low number of samples in protected areas (Figure 1B), probably because sampling in these areas requires a special permit. The limited number of samples does not allow performing more detailed analyses, for example, about the effect of climate on C stocks, which can be relevant because, as shown for *Nothofagus betuloides* in Table S1, within a forest type there may be important differences in the biomass C between regions.

TABLE 1 Forest carbon content (mean ± SD) in biomass (above- and below-ground) soil organic C (SOC), soil characteristics and total C stocks by forest type in the Chilean Patagonia.

Forest type	Biomass C ($Mg\,C\,ha^{-1}$)	# Biomass C samples[a]	SOC ($Mg\,C\,ha^{-1}$)	# SOC samples	Biomass C+SOC ($Mg\,C\,ha^{-1}$)	Max. Soil depth (cm)	Soil bulk density ($g\,cm^{-3}$)	Area (ha)	Total (10^6 Mg C)
Fitzroya cupressoides	124.8 ± 62.1	44	286.3	1	411.1	120	0.74	111 189	45.71
Austrocedrus chilensis	108.2 ± 58.7	38	269[b]	-	377.2	-	-	7472	2.82
Pilgerodendron uviferum	93.8 ± 42.9	14	296 ± 287	2	389.8	30	0.73	580 908	226.44
N. dombeyi–N. alpina–Laureliopsis philippiana	118.6 ± 58.2	337	424.8	1	543.4	61	0.70	175 517	95.38
Nothofagus betuloides	98.4 ± 39.6	160	232.3 ± 234	22	330.7	118	0.74	1 925 191	636.66
Nothofagus pumilio	116.4 ± 42.6	691	136.3 ± 132	131	252.7	120	0.72	3 017 087	762.42
N. obliqua–N. alpina–N. dombeyi	121.1 ± 52.3	751	142 ± 37	4	263.1	20	0.73	67 968	17.88
Evergreen	102.1 ± 43.7	791	367 ± 520	102	469.1	150	0.70	2 820 324	1323.01
Total	106.5[c]		250.8[c]		357.3[c]			8 705 656	3110.32

[a]Biomass C thematic maps are not differentiated by forest type *a priori*; therefore, the number of samples by forest type is referential.

[b]No data were available for *A. chilensis*, so the mean of all the other forest types was used.

[c]Mean C stock weighted by the area of each forest type.

Source: Biomass C data from the SIMEF platform (https://simef.minagri.gob.cl/descargas) based on Bahamondez et al. (2021); SOC data from Pfeiffer et al., 2020.

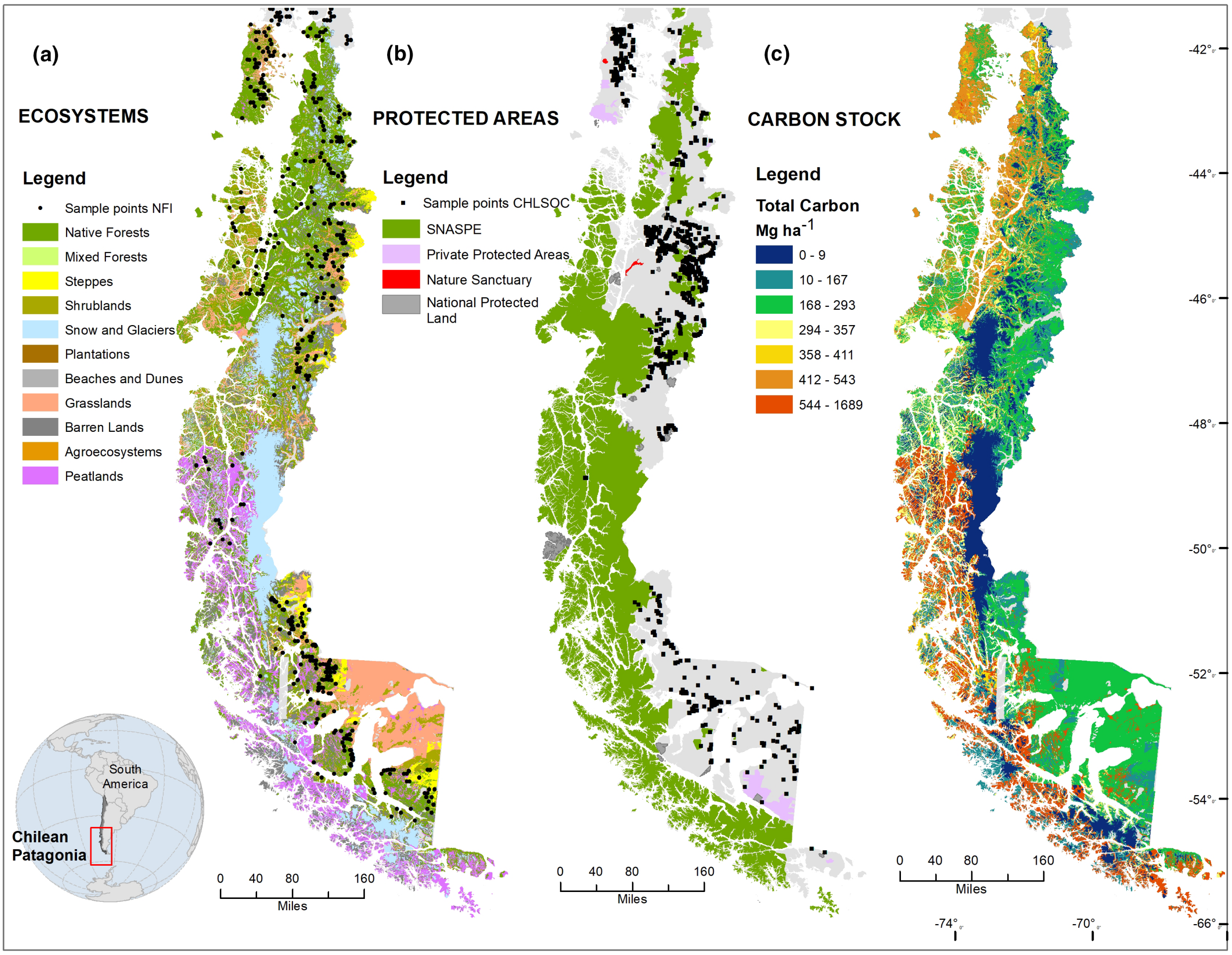

FIGURE 1 (a) Ecosystem types present in the Chilean Patagonia and the location of biomass carbon plots used from the National Forest Inventory (NFI). (b) Protected areas and the location of soil organic carbon samples from the CHLSOC database. (c) Total C stock (biomass + soil) in the terrestrial ecosystems of the Chilean Patagonia; data are taken from Table 1 for native forests and from Table 2 for the other ecosystem types; the maximum C stock reported for peatlands was used.

Carbon in biomass and soils by ecosystem type

While the lowest C stocks in biomass and soil were found in beaches and dunes, the ecosystems with the highest C stock (apart from peatlands) were native forests (357.3 Mg C ha^{-1}), which show a clear decrease when they are replaced by exotic plantations or agroecosystems (Table 2), as shown previously in northern Patagonia by Perez-Quezada et al. (2022). Provided these ecosystems are restored, the difference in stocks between natural and managed or degraded ecosystems can be used to estimate the potential mitigation of climate change.

Peatlands are the ecosystems that store more C in the soil per unit area (Table 2), followed by native forests and shrublands. In the case of peatlands, the mean SOC reported by Loisel and Yu (2013) of 1680 Mg C ha^{-1} is four times the mean value obtained from the CHLSOC database (406 Mg C ha^{-1}). This difference is likely explained because the mean and maximum soil depths in CHLSOC (0.92 and 2.44 m, respectively) are lower than those sampled by Loisel and Yu (2013) (between 2 and 12 m). The higher SOC value reported by Loisel and Yu (2013) is similar to the value of 1351 Mg C ha^{-1} that Yu (2012) reported for northern peatlands.

TABLE 2 Carbon content (mean ± SD) in biomass (above- and below-ground), soil organic C (SOC), soil characteristics and total C stock by ecosystem type.

Ecosystem type	Biomass C ($Mg\,ha^{-1}$)	Source	SOC ($Mg\,ha^{-1}$)	Soil samples	Biomass C+SOC (Mg C ha^{-1})	Max. Soil depth (cm)	Soil bulk density ($g\,cm^{-3}$)	Source	Area (ha)	Total C (10^6 Mg)
Native forests	106.5	a	250.8 ± 360	263	357.3	150	0.71	A	8705656	3110.32
Mixed forests	77.1	a[a]	216	—	293.1	150	0.73	A[a]	2581	0.76
Steppes	0.5	b	166 ± 141	83	166.5	116	1.12	A	635432	105.8
Shrublands	8.1	c	261 ± 303	477	269.1	216	0.86	A	4520150	1216.4
Glaciers and ice sheets	0	[b]	0	—		—	—	[b]	3572837	0
Plantations	47.7	d	182 ± 138	20	229.7	100	0.74	A	37820	8.7
Beaches and dunes	1.8	e	7.4	1	9.2	110	1.52	A	16080	0.15
Grasslands	3.5	c	232 ± 385	350	235.5	178	0.96	A	1066680	251.2
Barren lands	0	g	154 ± 114	11	154	100	0.68	A	3302374	508.6
Agroecosystems	2.8	c	115 ± 97	43	117.8	122	1.15	A	7685	0.9
Peatlands	8.6	f	406 ± 659	87	414.6	244	0.55	A	3394099	1407.2
			1680	22	1688.6	12	-	B		5731.3
Mean[c]	39.5		222.1		261.7					
			393.3		432.8					
Total[d]									25261394	6610
										10934

Note: Sources for Biomass C: (a) weighted average by the area of the different forest types in Table 1; (b) Ahumada and Faúndez (2001); (c) Perez-Quezada et al. (2022); (d) Dube et al. (2012); (e) Liliana Vásquez (unpublished data); and (f) Cabezas et al. (2015). Sources for SOC: (A) Pfeiffer et al., 2020, and (B) maximum value from Loisel and Yu (2013).

[a]Estimated as the average of native forests and plantations.

[b]Assumed to be zero.

[c]Mean C stock weighted by the area of each ecosystem type (the upper value considers the minimum C content reported for peatlands, while the bottom value considers the maximum).

[d]The total C was estimated considering the mean SOC content for all ecosystems and the minimum C content reported for peatlands (upper value) and the maximum C content (bottom value).

The Chilean Patagonia is mainly covered by native forests (34%), while shrublands, glaciers and ice sheets, peatlands and barren lands cover somewhat a similar area (13%–18%, Table 2). The reported values for forests, although unbiased, lack precision due to the low number of sampling points, given by budget restrictions.

Total carbon stocks in the Chilean Patagonia and the role of protected areas

Evergreen and *N. pumilio* forests have the highest regional C stock, which is mainly explained by the high area they cover in the region (Table 1, Figure 1). While some ecosystems have been more extensively sampled, others have not, even though they cover vast territories. This is the case of shrublands and grasslands for biomass C and barren lands for SOC (Table 2). This is relevant in the latter case because even though the biomass C stock was assumed to be zero for this ecosystem type, soil data show that they can store important amounts of C (~150 Mg C ha^{-1}). Similarly, it seems relevant to analyse data on necromass, as this pool can be important in some ecosystems (e.g. old-growth forests, González et al., 2022). The NFI does account for dead-standing or fallen trees, but these data were not available at the time of this publication, implying that the contribution of necromass could increase the total C stock of forest ecosystems.

Native forests cover 8.7×10^6 ha and store 3110×10^6 Mg C, being the ecosystem with highest area and C stock. Meanwhile, peatlands cover about 3.4×10^6 ha and store 1407 10^6 Mg C if the mean value of the CHLSOC database is used for the soil pool. However, if the value reported by Loisel and Yu (2013) is used, the total C stored in peatlands is estimated at 5731×10^6 Mg C. This implies a mean total ecosystem stock in the region of 261.7 and 432.8 Mg C ha^{-1}, respectively, with a range between 0 and 1689 Mg C ha^{-1} (Figure 1C), and a total C stored range between 6.6 and 10.9 Pg C (1 Petagram (Pg) = 10^{15} g).

The high amount of C stored in the Chilean Patagonia makes its protection highly relevant for the climate change adaptation strategy of the country. Moreover, this area contains unique endemic species and ecosystems, so its protection is also relevant to fight the biodiversity global crisis. The State protected areas cover 52.9% of the area and store 58.9% of the C, while private protected areas cover 2.0% of the area and store 2.1% of the C. This means that 54.9% of the Chilean Patagonia is protected (Figure 1B), representing 61% of the C stock in this area (see Table S2 for detailed information). The mean value of C stored in national parks in this area is 508 Mg C ha^{-1}, which is almost double the amount stored in undisturbed forests in the Amazon (276.2, Berenguer et al., 2014). Although these figures seem high, Chile can still move forward in the preservation of its natural resources, particularly by approving a legal framework that was proposed to protect its soils (Salazar et al., 2022).

CONCLUSIONS

The most relevant ecosystems in terms of C stored in the Chilean Patagonia are forests and peatlands. Databases that provide information about C stored in biomass and soils contain essential information to estimate the C stored by terrestrial ecosystems in this area. However, large information gaps still exist, generating uncertainties particularly related to

(a) information about C stored in forests and particularly in other ecosystems' biomass is notably scarce; (b) ecosystems are unevenly represented in terms of soil organic carbon samples; and (c) necromass is usually not included when sampling C storage, although some data exist in the case of forests.

The total C stored per hectare in national parks in this area is almost twice the value reported for undisturbed forests in the Amazon. State PAs store most of the C in this area and the private PAs a very low proportion, which makes a call for the private sector to increase their contribution to C storage. The relevance of native forests and peatlands in terms of C storage makes it a priority to have a more precise estimation of the C stocks in these types of ecosystems.

AUTHOR CONTRIBUTIONS

Jorge Perez-Quezada: Conceptualization (equal); funding acquisition (equal); methodology (equal); writing – original draft (equal); writing – review and editing (equal). **Macarena Moncada:** Formal analysis (equal); investigation (equal); methodology (equal); software (equal); writing – original draft (equal); writing – review and editing (equal). **Patricio Barrales:** Formal analysis (equal); investigation (equal); methodology (equal); software (equal); writing – original draft (equal). **Rocío Urrutia-Jalabert:** Methodology (equal); writing – review and editing (equal). **Marco Pfeiffer:** Data curation (equal); methodology (equal); writing – review and editing (equal). **Aldo Farías Herrera:** Conceptualization (equal); funding acquisition (equal); software (equal); writing – review and editing (equal). **Rodrigo Sagardía:** Data curation (equal); investigation (equal); methodology (equal); writing – review and editing (equal).

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DATA AVAILABILITY STATEMENT

All data used in this work are available in public databases.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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