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Current and potential carbon storage in soils of Chilean Patagonia

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Introduction: Climate change mitigation increasingly relies on enhancing soil organic carbon (SOC) storage, particularly in soils with strong mineral stabilization mechanisms. This study aimed to quantify the current and potential SOC storage capacity of volcanic soils.

Methods: A national soil database covering the Chilean latitudinal gradient ($n = 1,660$) was used to develop quantile regression models relating SOC to Al_a in order to estimate upper and lower SOC storage thresholds. These models were then applied to soils from the Aysén Region under different land uses ($n = 173$) to evaluate current SOC stocks relative to their storage potential.

Results: Results indicated that approaches based on soil texture were inadequate for estimating SOC storage in volcanic soils, highlighting the importance of mineral reactivity indicators such as Al_a . SOC storage potential increased with soil reactivity, with the highest potential values observed in soils with $Al_a > 600$ mg kg^{-1} . Soils in the Aysén Region showed a high SOC storage potential, averaging 358 t C ha^{-1} , yet current stocks were on average 33.5% below this capacity. Agricultural crops and grasslands exhibited the largest gaps between current and potential SOC stocks, whereas wetlands and peatlands were close to or exceeded their estimated storage capacity due to hydromorphic conditions.

Discussion: These findings demonstrate the high carbon sequestration potential of volcanic soils in southern Chile and highlight the importance of mineralogical controls, particularly reactive aluminum, in regulating SOC stabilization and informing land management strategies aimed at increasing soil carbon storage.

KEYWORDS

extractable aluminium, land use, soil ecosystem function, soil mineral reactivity, volcanic soils

1 Introduction

One of the key functions of soil is its ability to accumulate, store, and sequester carbon (European Commission, 2006), a process that not only influences climate regulation, but also affects other ecosystem functions (Wiesmeier et al., 2019). Soil organic carbon (SOC) accumulation depends primarily on soil organic matter (SOM) dynamics (Jenkinson et al., 1992; Ros et al., 2011), which depend on the balance between carbon inputs and losses, as well as the SOC turnover rate (Cotrufo and Lavelle, 2022). This turnover rate is influenced by factors such as: (i) the bioavailability of organic residues added to the soil (Gunina et al., 2017), (ii) edaphoclimatic conditions (Krull et al., 2003; Wiesmeier et al., 2019), and (iii) soil

carbon stabilization mechanisms, including aggregation, adsorption, and the formation of organo-mineral or organo-metallic complexes (Krull et al., 2003; López-Ulloa et al., 2005; von Lützow et al., 2008; Hoffland et al., 2020). In this context, at least two SOC fractions can be distinguished based on their turnover rate: i) the labile fraction, which has a high bioavailability and accessibility to soil microorganisms (Oechel et al., 1998; Wickland et al., 2001; Wang C. et al., 2022), and ii) the stabilized fraction, which has recalcitrant organic matter (OM) and organic carbon strongly associated with Al and Fe on the mineral surface, with a long residence time in the soil (Shi et al., 2023). This fraction is related to soil reactivity (colloidal fraction), resulting in chemical C stabilization and physical protection through aggregation, preventing microorganisms access to the degradation of OM (Zunino et al., 1982; Ros et al., 2011; Yudina and Kuzyakov, 2023).

Soil properties can be classified as either inherent or dynamic, depending on their origin, evolution, and response to environmental or management changes (Dominati et al., 2010; Bagnall et al., 2023). Inherent properties, determined by soil formation factors and processes, are relatively stable and establish a physicochemical limit for dynamic properties, which can vary over time due to natural processes or human activities. In this sense, the SOC storage capacity is strongly influenced by soil mineralogy and texture (Hassink, 1997; Matus et al., 2006; Wiesmeier et al., 2019). At a global scale, soil texture, particularly the content of fine fractions (<50 μm or <20 μm), has been established as a key indicator of soil reactivity, showing a direct and positive relationship with the capacity to store, accumulate, and sequester SOC (Hassink, 1997). Nonetheless, this behavior is not uniform across all soil types. In volcanic soils, for example, mineralogical characteristics derived from parent material confer unique properties that influence C storage capacity (Percival et al., 2000; Matus et al., 2006; Parada et al., 2024; Matus et al., 2024). In these soils, C storage capacity is more closely related to mineralogy-driven reactivity than texture (Matus, 2021; Clunes et al., 2022a). It has thus been proposed to consider chemical reactivity indices to estimate the C storage capacity of volcanic soils, such as ammonium acetate-extractable aluminum pH 4.8 (Al_a). The use of Al_a as an indicator of soil reactivity (as a weighted factor between the colloid content of the soil and the quality of the colloid) has been widely used in high correlation with SOC in volcanic soils (Matus et al., 2008; Matus et al., 2014; Valle et al., 2015; Clunes and Pinochet, 2020; Matus et al., 2024). This method also has many advantages; it is simple, repeatable, and inexpensive, allowing large quantities of soil to be characterized according to their reactivity.

The growing need to develop public policies that promote the sustainable use of natural resources has driven the scientific community to develop methodologies for quantifying soil ecosystem functions (Baveye et al., 2016). However, direct evaluation methods are often costly and time-consuming, leading to the search for alternative approaches. In this context, Vogel et al. (2019) proposed a methodological framework based on indicators to estimate both the intrinsic potential and the current state of an ecosystem function. The intrinsic potential has been defined as the maximum capacity a soil can provide, measured through inherent properties associated with the evaluated function, while also considering site conditions such as climate and topography. On the other hand, the current state is determined by dynamic properties, which reflect the present conditions of the soil. This

approach represents an efficient alternative for assessing key ecosystem functions, such as SOC storage, without incurring the high costs associated with traditional methods.

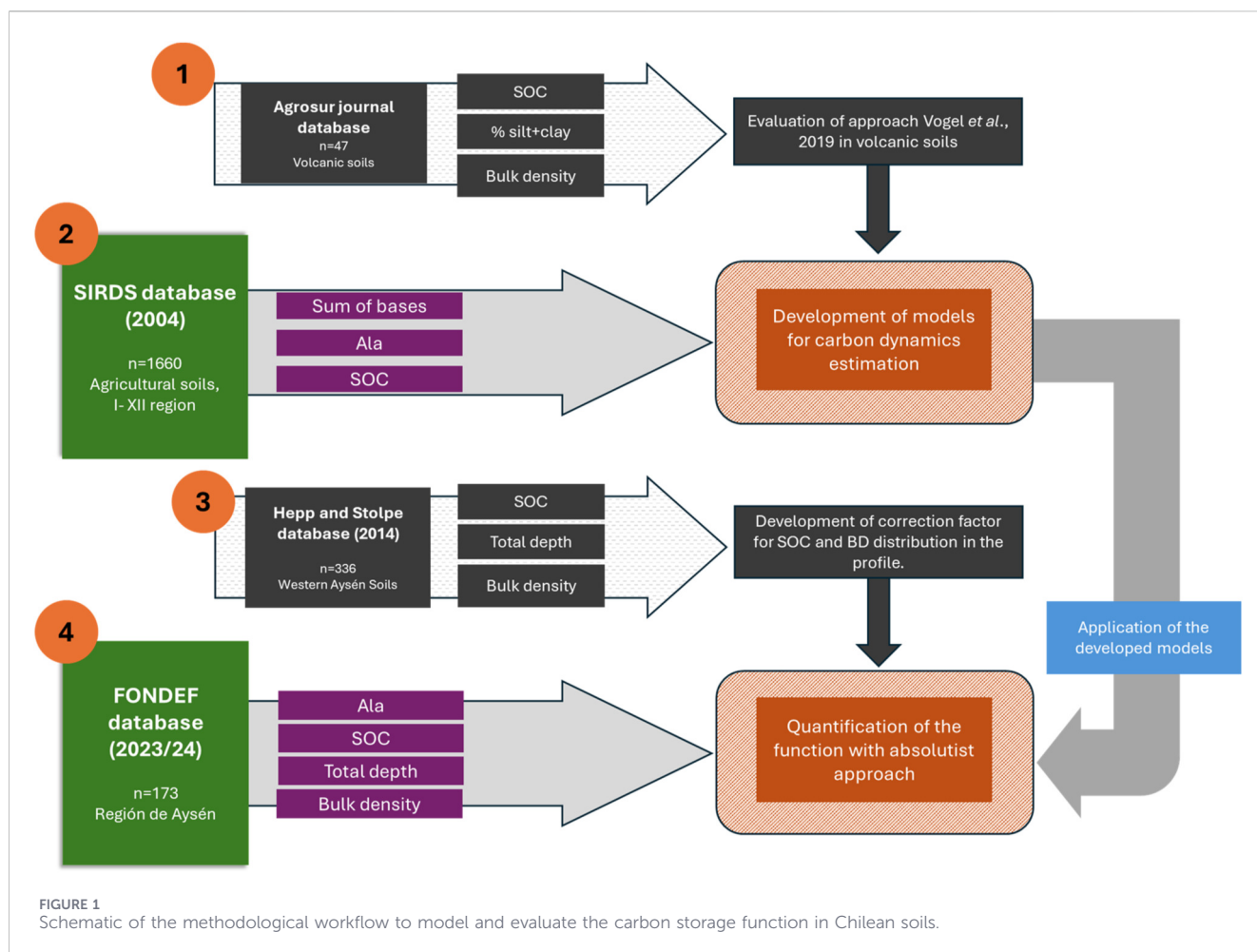
In this scenario, the Aysén Region, located in southern Chile, emerges as a highly relevant area due to its vast pristine landscapes and diverse vegetation, which respond to the region's climatic variations, where precipitation and temperature change significantly along a transverse gradient from east to west (Hepp and Stolpe, 2014). Additionally, geological processes, such as glaciation and volcanic material deposition, combined with a rugged topography, have favored the development of a highly diverse range of soils (Luzio, 2010). These characteristics make this region an ideal setting for evaluating SOC storage function, considering the intrinsic potential of a wide diversity of soils (Supplementary Table S1) with a broad range of SOC contents (Supplementary Table S4). Therefore, this study hypothesized that soil reactivity, determined by inherent properties related to the colloidal fraction, is a key indicator for quantifying the SOC storage function. Consequently, with the use of a soil reactivity index, both the intrinsic potential and the current SOC storage of Aysén Region soils were described. Therefore, the objective of this study was to evaluate the SOC storage function (potential and current) across different soils and vegetation covers in the Aysén Region using the reactivity index as a fundamental parameter for classification. Mathematical models based on Chilean soil data were developed to quantitatively assess this function and compare the reactivity of the colloidal fractions of soils, which were estimated using a chemical soil indicator (Al_a). Subsequently, model parameters were adjusted to the specific edaphic conditions of the region.

2 Materials and methods

2.1 Study area: Aysén Region

The Aysén Region (Supplementary Figure S1), located in the Chilean Patagonia (southern), covers approximately 108,494 km and is characterized by a low population density (0.8 inhabitants km^{-1}) and a predominantly rural landscape (93% of the total area) (ODEPA, 2021). Its economy relies primarily on activities such as raising livestock, tourism, and marine resource exploitation. At the beginning of the 20th century, land-clearing fires affected 3 million hectares, primarily in valleys (Hepp and Stolpe, 2014). According to the National Forestry Corporation (CONAF) (2020), 40.9% of the region is covered by native forests, 25.9% by grasslands and shrublands, 14.5% by snow and glaciers, and 12.9% by areas devoid of vegetation. Additionally, water bodies (4.2%), wetlands (1%), exotic tree plantations (0.3%), agricultural lands (0.07%), urban and industrial areas (0.03%), and mixed forests (0.01%) are present.

This region exhibits diverse morphological features, including mountains, valleys, rivers, and fjords. Fluvio-glacial deposits predominate in the north, while the south is characterized by fluvial erosion and a more rugged topography (Casanova et al., 2013). Climate conditions vary depending on the slope of the Andes Mountains: the western slope is wetter, with an annual precipitation of up to 3,898 mm, and mean temperatures of 9 °C, whereas the eastern slope is drier, with an annual precipitation of 564 mm and mean temperatures of 6.4 °C (Hepp, 2019). These conditions result



in four agroclimatic zones: coastal or insular, humid, intermediate, and steppe, along with diverse areas with microclimates (Hepp and Stolpe, 2014). Andisols, associated with morainic, fluvio-glacial, and alluvial deposits (Luzio, 2010) predominate, alongside Entisols, Inceptisols, Spodosols, Histosols, and Mollisols (Hepp and Stolpe, 2014). Considering the aforementioned factors, evaluating the SOC function in the Aysén Region is crucial due to its edaphoclimatic diversity and the presence of pristine ecosystems.

2.2 Databases used to assess the soil C storage function

This study utilized four databases (BS-1, BS-2, BS-3 and BS-4; Figure 1) to model and evaluate the soil C storage function in Chilean soils, focusing on volcanic soils in the Aysén Region.

First, the approach proposed by Vogel et al. (2019) was assessed in volcanic soils using a database (BS-1) comprised of 47 records published between 1973 and 2016 in the *Agro Sur* journal (ISSN 0719-4196). This database allowed us to examine the relationships between soil texture and organic carbon content in volcanic soils. Subsequently, to develop quantile regression models that related organic carbon content to the reactivity indicator, a second database (BS-2) from the Chilean Degraded Soils Recovery Program (Sistema de Incentivos para la Sustentabilidad Agroambiental de los Suelos Agropecuarios (SIRSD), 2004) was employed. This

dataset, which contained 1,660 soil samples collected from the Arica and Parinacota Region (I) to the Magallanes Region (XII), facilitated the estimation of critical carbon storage levels for major soil groups at the national level.

Next, correction factors specific to the organic carbon distributions and bulk densities of soils in the Aysén Region were developed. For this purpose, a third database (BS-3) was used, comprised of 64 soil profiles reflecting the organic carbon distribution factor and 50 for the bulk density factor. These data were based on morphological descriptions and laboratory analyses of soil profiles published by the National Institute for Agricultural Research (INIA) (Stolpe and Hepp, 2014). These correction factors were then used to adjust carbon storage function estimates to the specific characteristics of different soils in the Aysén Region.

Finally, the developed models and correction factors were applied to a fourth database (BS-4), with 173 samples collected as part of a FONDEF project (2023/2024). This database allowed for the evaluation of both the potential and current state of the soil carbon storage function in soils throughout the Aysén Region.

2.3 Evaluation of an existing SOC storage estimation model

To assess the applicability of the Vogel et al. (2019) approach in volcanic soils, the BS-1 database, containing data on organic carbon

TABLE 1 Functionality indices for organic carbon storage adapted from Vogel et al. (2019).

Name indicator	Symbol	Units	Equations
Potential carbon storage	C _p	kg m ⁻²	(C _{max} *10)*Bd*h*fSOC
Intrinsic potential index	I _{soc}	Unitless	$\frac{1}{C_{model}} * C_{max}$
Current carbon storage	C _s	kg m ⁻²	(SOC*10)*Bd*h*fSOC
Current state index	Î _{soc}	Unitless	$\frac{C_s - (C_{inert} * 10 * Bd * h)}{C_p}$

content, soil texture, fine particle content (<50 µm), and bulk density was utilized. Based on these data, the original equations proposed by Vogel et al. (2019) were applied to calculate the indices of the soil carbon storage function (Table 1), including both the current state (C_s) and its dimensionless index (Î_{soc}), as well as the intrinsic potential (C_p) and its respective index (I_{soc}). The equation for C_p was adjusted according to the authors' specific recommendations for particles smaller than 50 µm (Equation 1).

$$C_p = (7.18 + 0.20 T) \rho_b d (1 - V_s) \tag{1}$$

Where T is the percentage of particles <50 µm (%), ρ_b is the bulk density (g cm⁻³), d is the topsoil depth (dm) and V_s is the volume of rock fragments >2 mm (%) (Vogel et al., 2019).

2.4 Testing SOC dynamics models

To assess carbon storage in agricultural soils at a depth of 20 cm, samples from BS-2 were classified into three groups based on the Al_a: soils with <200 mg kg⁻¹ (n = 713), those between 200 and 600 mg kg⁻¹ (n = 279), and those with >600 mg kg⁻¹ (n = 668). This classification assumes that these groups exhibit distinct behaviors due to their clay dominance, estimated from Al_a values correlated with SOC in soils. Thus, Al_a is considered an indicator of reactivity (Matus et al., 2008; Clunes and Pinochet, 2020; Rodríguez, 1993). According to a study by the Agricultural Studies and Policy Office (ODEPA, 2024), soils with Al_a < 200 mg kg⁻¹ primarily consist of mineral soils dominated by crystalline clays and organic soils. Those with Al_a between 200 and 600 mg kg⁻¹ are associated with older volcanic or clayey brown materials, whereas soils with Al_a > 600 mg kg⁻¹ are typically mature and recent "Trumaos", "Ñadis", and Podzols.

2.5 Potential and current state of the carbon storage function

The carbon storage function was quantified using equations derived from models developed with quantile regressions that adapted the Vogel et al. (2019) approach for volcanic soils. The results were adjusted using correction factors specific to Aysén Region soils (BS-3; Figure 1), based on chemical and physical properties assessed in laboratory analyses of samples collected from different geographic locations and vegetation covers (BS-4; Supplementary Table S3).

A total of 173 soil samples were collected from various locations in the Aysén Region (BS-4). Vegetation covers were grouped into eight categories: forests and tree-covered areas, including samples from primary native forests ("Lenga" (*Nothofagus pumilio*) and

"Ñirre" (*Nothofagus antarctica*)) and secondary regrowth (n = 47); agricultural crops, including species such as alfalfa, oats, and turnip (n = 6); shrubs and bushes, including samples from "Murtilla" (*Ugni molinae*) and shrubland (n = 19); grasslands, including "Coirón" (*Festuca* spp.) and mixed pastures (n = 75); wetlands and swamps, including peat bogs locally referred to as "Mallines" and peat bogs (n = 9); riparian vegetation, with samples from reeds and wet meadows (n = 5); silvicultural crops, including samples from pine plantations (n = 10); and others, comprising samples from subdivided land and hillsides (n = 2).

The analyzed soil properties included Al_a (mg kg⁻¹) (Sadzawka et al., 2006), SOC determined using the Walkley-Black method (g C 100 g⁻¹) (Sadzawka et al., 2006), bulk density (g cm⁻³) (Bd) (Day, 1965), and total depth (dm; Supplementary Table S4). The first three properties were evaluated in the top 20 cm (0.2 dm) of the soil profile, while total depth was recorded up to 10 dm. In cases where the soil profile exceeded this depth, a value of 11 dm was assumed.

According to the classification based on Al_a content, the regional sampling included 49 soils with an Al_a content of <200 mg kg⁻¹, 36 samples with an Al_a content between 200–600 mg kg⁻¹, and 88 samples with an Al_a content of >600 mg kg⁻¹.

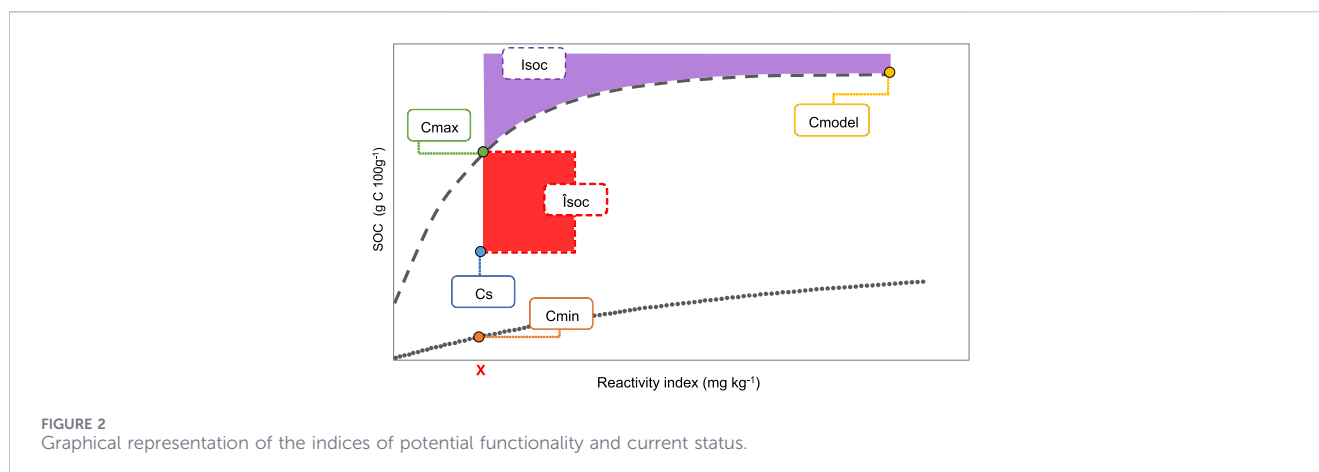
2.6 Development of correction factors for organic carbon and bulk density with depth

To model the depth distribution dynamics of the total soil organic carbon contents (fSOC) and bulk densities (fBd) in soils of the Aysén Region correction factors using the BS-3 dataset were developed for these properties (Supplementary Figures S2,S3). This dataset was derived from the characterization of 69 soil profiles described in the article "Characterization and Properties of the Soils of Western Patagonia" (Aysén) (Stolpe and Hepp, 2014), representing soil orders such as Andisol, Entisol, Inceptisol, Spodosol, Histosol, and Mollisol (Supplementary Table S1).

A total of 64 profiles and 294 horizons were selected for fSOC calculation, and 50 profiles and 239 horizons for fBd (Supplementary Table S1), after excluding incomplete or insufficient data. Values were adjusted to a reference depth of 40 cm and organized into 17 depth intervals of 10 cm, ranging from [0–10 cm] to [160–170 cm]; outliers were removed. To optimize correction factors, logarithmic functions were evaluated for fSOC, and cubic functions for fBd, across different distribution quartiles (see Supplementary Figures S2,S3). The functions with the lowest mean squared error (MSE) were selected.

2.7 Quantification of the soil organic carbon storage function

The potential carbon storage capacity (C_p), according to Vogel et al. (2019), represents the soil's intrinsic maximum capacity to store carbon (Table 1), determined by its inherent properties. It defines the upper critical level for soil organic carbon storage (Figure 2). This potential is measured using the potential storage index (I_{soc}), which ranges from 0 to 1, where values close to 1 indicate soils with a higher storage capacity relative to the maximum established by the model (C model) developed in Section 2.3.



Conversely, the current state (C_s) was calculated based on the SOC content measured in the laboratory, considering it as a dynamic property. The current state index ($\hat{I} \text{ soc}$) permitted a comparison between the current storage and its intrinsic potential, where values close to 1 reflect a state near the soil's maximum potential. Additionally, a lower critical level (C_{min}) was established to represent the minimum threshold of organic carbon required to maintain soil functionality associated with ecosystem services. This lower critical level may help identify severe degradation scenarios, where the soil loses its capacity to recover its initial conditions.

2.8 Statistical analysis

Quantile regressions are widely used in other areas of science when one wants to separate values that differ from the mean, using extreme values to adjust regressions between an independent and dependent variable, either with their minimum or maximum values (Koenker, 2005). Quantile regressions were thus employed to model the relationship between SOC and Al_a . The analyses were performed using a combination of Python and Microsoft Excel tools. Nonlinear quantile regression models were implemented in Python, using the *pandas* libraries for data manipulation, *NumPy* for numerical calculations, *SciPy* for parameter optimization, and *matplotlib* for visualization. The models were adjusted to exponential and Langmuir functions at different percentiles (p1 to p99) to establish minimum and maximum thresholds for the organic carbon storage of large soil groups in Chile.

In Excel, the BS-1 database allowed us to evaluate the direct applicability of the approach used by Vogel et al. (2019) in volcanic soils. Once the equations were determined, their performance was evaluated using the adjusted mean squared error (MSEa), calculated only with observations above or below the regression curves according to upper or lower thresholds, selecting the models with the lowest error and highest conceptual consistency. With the BS-3 database, correction factors were constructed from the quartiles by depth, adjusting logarithmic and cubic equations, evaluated according to their MSE and R^2 , choosing those with the best fit to adapt the equations to the soil conditions of the Aysén Region. Finally, the BS-4 database was used to estimate the current and potential state of the carbon storage function in soils of the Aysén Region (Table 1).

3 Results

3.1 Evaluation of the Vogel et al. (2019) approach in Chilean volcanic soils

The approach proposed by Vogel et al. (2019) was found to be unsuitable for quantifying the carbon storage function in volcanic soils. The maximum C_p value obtained from the data was 30.9 mg g^{-1} (3.1%), which is significantly lower than the values commonly found in volcanic soils. As shown in Figure 3, C_s was found to be at least ten times higher than the C_p value calculated.

These results suggest that using soil texture as an indicator to quantify organic carbon storage in volcanic soils is not appropriate. Therefore, the specific characteristics of Chilean volcanic soils were incorporated in an adaptation of the Vogel et al. (2019) approach.

3.2 Development of models for estimating critical carbon storage limits in soils

Exponential models exhibited more errors ($MSEa = 3160.7$) than parabolic models ($MSEa = 2645.6$). However, exponential models (Table 2) were selected as the most appropriate because the parabolic models obtained after iterations presented negative intercepts at low percentiles (p1 and p5), which is conceptually inappropriate. Although this could have been solved by setting the intercept to zero, this would have contradicted with the empirical approach of this study.

To define the critical carbon storage levels, percentiles p5 (lower limit) and p95 (upper limit) were selected, thereby avoiding overfitting associated with extreme percentiles (p1 and p99). These values identified soils with a saturation potential (p95) and those at risk of degradation (p5). Additionally, models fitted at percentiles p10 and p90 could be used as alternatives for a more rigorous evaluation, narrowing the critical levels (Figure 4).

A total of 12.6% of the BS-2 (209 samples) fell outside the p5/p95 models, with 6.5% of the dataset below p5 and 6.1% above p95. Among the data below p5, 56.5% corresponded to soils with $>600 \text{ Al}_a$, 35.2% to soils with $<200 \text{ Al}_a$, and 8.3% to soils with $200\text{--}600 \text{ Al}_a$. Meanwhile, the data above p95 were mostly from soils with $>600 \text{ Al}_a$ (63.4%), followed by soils with $<200 \text{ Al}_a$ (30.7%) and those with $200\text{--}600 \text{ Al}_a$ (5.9%). In comparison, the p10/p90 models excluded a

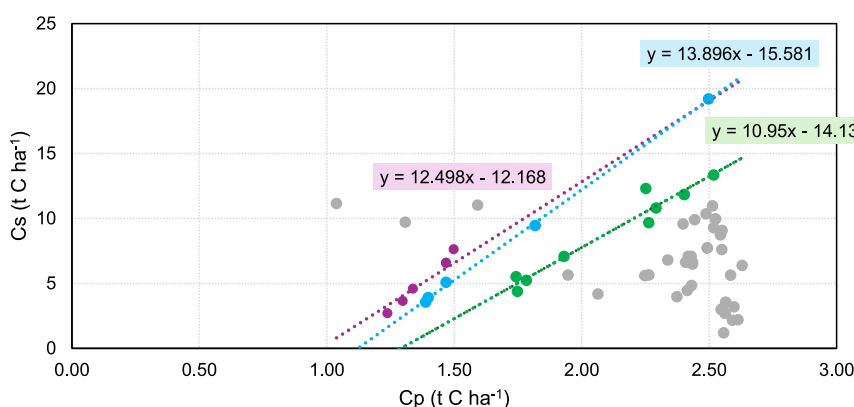


FIGURE 3 Relationship between potential carbon stock (Cp) and current stored carbon stock (Cs) in volcanic soils taken from the Agrosur journal (BS-1), calculated using the equations proposed by Vogel et al. (2019). Each color corresponds to a different level of fitting, using different point groups to assess the slope variability in the application of the equation from Vogel et al. (2019).

TABLE 2 Models generated using quantile regression adjusted to an exponential function for estimating carbon storage in soils.

Percentile	Model equation	MSEa	RMSE	Number of points used for error calculation
1	$34.9 \cdot (1 - \text{EXP}(-0.00007 \cdot \text{Al}_a)) + 0.04$	3.4	1.9	16 (0.96%)
5	$26.2 \cdot (1 - \text{EXP}(-0.00017 \cdot \text{Al}_a)) + 0.22$	75.8	8.7	83
10	$21.4 \cdot (1 - \text{EXP}(-0.00024 \cdot \text{Al}_a)) + 0.43$	174.3	13.2	166
20	$15.9 \cdot (1 - \text{EXP}(-0.00041 \cdot \text{Al}_a)) + 0.68$	489.4	22.1	333
30	$16.4 \cdot (1 - \text{EXP}(-0.00044 \cdot \text{Al}_a)) + 0.88$	966.7	31.1	498
40	$15.8 \cdot (1 - \text{EXP}(-0.00050 \cdot \text{Al}_a)) + 1.15$	1647.3	40.6	663
50	$15.4 \cdot (1 - \text{EXP}(-0.00057 \cdot \text{Al}_a)) + 1.37$	2653.8	51.5	829
60	$16.7 \cdot (1 - \text{EXP}(-0.00056 \cdot \text{Al}_a)) + 1.72$	11,571.8	107.6	665
70	$14.7 \cdot (1 - \text{EXP}(-0.00069 \cdot \text{Al}_a)) + 2.29$	9226.1	96.1	498
80	$13.6 \cdot (1 - \text{EXP}(-0.00083 \cdot \text{Al}_a)) + 3.04$	7172.2	84.7	332
90	$10.8 \cdot (1 - \text{EXP}(-0.00094 \cdot \text{Al}_a)) + 5.58$	4406.6	66.4	173
95	$10.3 \cdot (1 - \text{EXP}(-0.0012 \cdot \text{Al}_a)) + 8.06$	2175.8	46.6	74
99	$13.1 \cdot (1 - \text{EXP}(-0.0012 \cdot \text{Al}_a)) + 11.61$	526.1	22.9	20

larger portion of the dataset (27.5% of total BS-2, 456 samples). These outliers from the p10/p90 models mainly corresponded to soils with $>600 \text{ Al}_a$ (38.9%), $<200 \text{ Al}_a$ (21.6%), and $200\text{--}600 \text{ Al}_a$ (15.1%). Although the number of data points falling outside the limits was higher in these models, the distribution of soil types remained similar to that observed in the p5/p95 models.

3.3 Evaluating carbon storage

According to functionality indices, soils in the Aysén Region demonstrated a carbon storage capacity (Cp) of $358 \pm 133 \text{ t C ha}^{-1}$, with a range of [40–734], placing them in a medium-to-high potential range compared to other Chilean soils. The carbon storage potential index (I soc) was 0.71 ± 0.10 [0.45–0.98]. However, these soils are currently storing 33.5% less carbon than

their potential capacity, with a current storage (Cs) averaging $238 \pm 120 \text{ t C ha}^{-1}$ [14–712], and an I soc of 0.59 ± 0.60 [–0.08; 4.95].

3.3.1 Role of Al_a in current and potential SOC storage

Soils with $\text{Al}_a >600 \text{ mg kg}^{-1}$ demonstrated the highest potential carbon storage capacity (Cp), with an average of $410 \pm 122 \text{ t C ha}^{-1}$, followed by soils with $\text{Al}_a <200 \text{ mg kg}^{-1}$ (–19.8% of soils with $\text{Al}_a >600$) and soils with Al_a between 200 and 600 mg kg^{-1} (–32.9% of soils with $\text{Al}_a >600$). Regarding the current carbon storage state (Cs), soils with $\text{Al}_a >600 \text{ mg kg}^{-1}$ stored, on average, $284 \pm 120 \text{ t C ha}^{-1}$, while soils with Al_a between 200– 600 mg kg^{-1} and $<200 \text{ mg kg}^{-1}$ stored between 22.2% and 40.4% less than soils $>600 \text{ mg kg}^{-1}$, respectively (Figure 5).

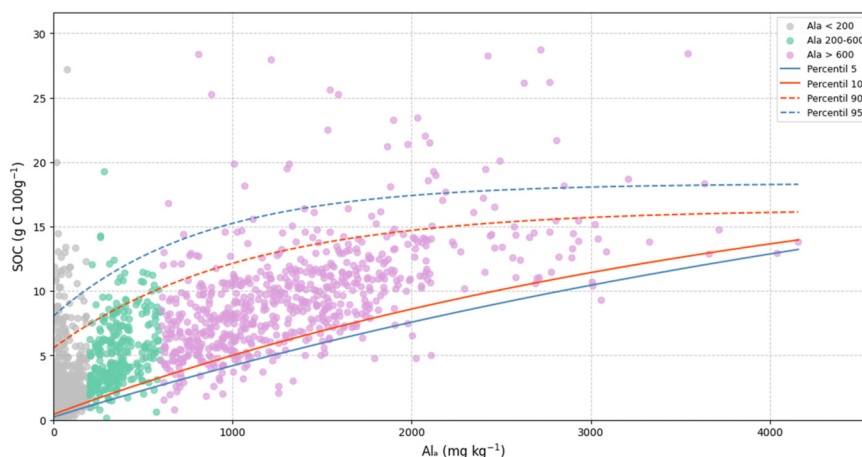


FIGURE 4 Quantile regression models fitted to an exponential function for estimating carbon storage. Selected models (p5/p95; blue lines) and alternative models (p10/p90; red lines).

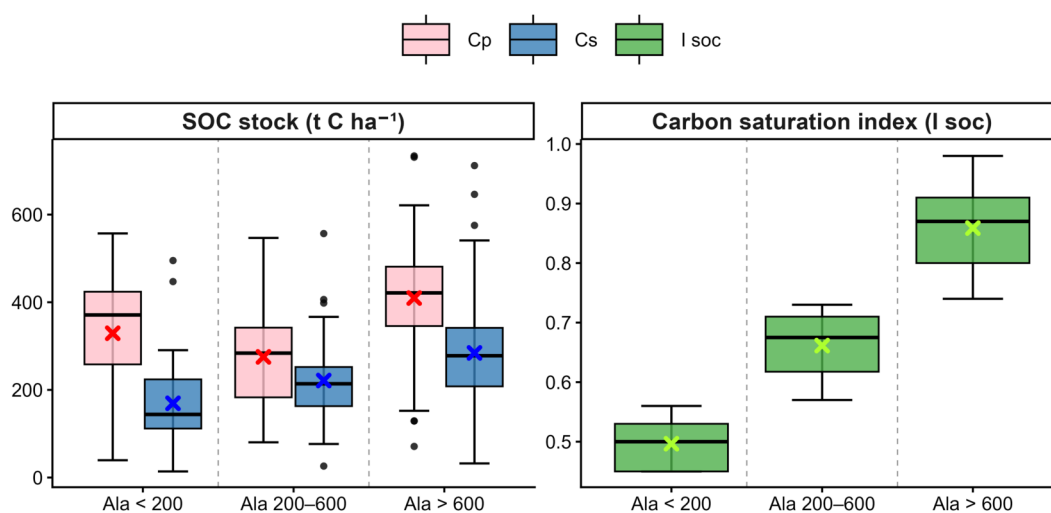


FIGURE 5 Distribution of carbon storage functionality indices in soils of the Aysén Region according to Al_a content.

Soils with $Al_a < 200 \text{ mg kg}^{-1}$ presented the maximum value of $\hat{I} \text{ soc}$ (4.9) and a higher frequency of outliers, suggesting that these soils have been exposed to conditions favoring carbon accumulation above expected levels. In addition, more than 25% of the soils with Al_a between 200–600 mg kg^{-1} exceeded the threshold of $\hat{I} \text{ soc} = 1$, indicating that in these cases carbon accumulation could exceed its intrinsic capacity. On the other hand, only two negative $\hat{I} \text{ soc}$ values were found, both in soils with $Al_a > 600 \text{ mg kg}^{-1}$, indicating possibly severe degradation in these soils.

3.3.2 Current and potential status of the carbon storage function according to the type of vegetation cover in the Aysén Region

Soils with the highest potential carbon storage capacity (C_p) were found under grasslands ($436 \pm 83 \text{ t C ha}^{-1}$), agricultural crops

($401 \pm 40 \text{ t C ha}^{-1}$) and silvicultural crops ($382 \pm 64 \text{ t C ha}^{-1}$). In contrast, soils with the lowest capacity were those under forests and woodlands ($300 \pm 134 \text{ t C ha}^{-1}$), riparian vegetation” ($200 \pm 169 \text{ t C ha}^{-1}$) and wetlands and marshes ($115 \pm 54 \text{ t C ha}^{-1}$) (Figure 6).

In terms of the intrinsic potential index ($I \text{ soc}$), soils under the category others (0.81 ± 0.12) and grasslands (0.78 ± 0.16) showed the highest values, close to the theoretical maximum (C_{max}). On the other hand, soils under silvicultural crops (0.59 ± 0.12), riparian vegetation (0.54 ± 0.09) and agricultural crops (0.53 ± 0.15) showed the lowest values.

Regarding the current carbon (C_s) storage status, soils under grasslands stored, on average, $278 \pm 112 \text{ t C ha}^{-1}$, followed by shrublands and shrubs ($237 \pm 137 \text{ t C ha}^{-1}$) and forests and woodlands ($221 \pm 130 \text{ t C ha}^{-1}$). The lowest values were observed

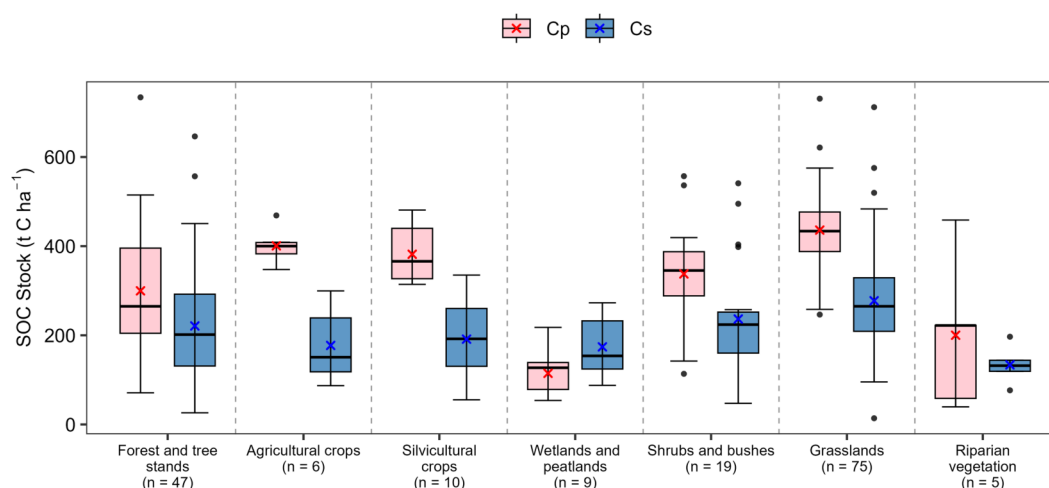


FIGURE 6
Distribution of potential capacity (Cp) and current state (Cs) of carbon storage according to vegetation cover type in the Aysén Region.

in agricultural crops ($177 \pm 86 \text{ t C ha}^{-1}$), wetlands and marshes ($177 \pm 67 \text{ t C ha}^{-1}$) and riparian vegetation ($134 \pm 44 \text{ t C ha}^{-1}$). The gaps between Cp and Cs varied according to the type of vegetation cover. Agricultural crops presented the largest gap, with 224 t C ha^{-1} (55.9% of its potential was unused), followed by silvicultural crops (191 t C ha^{-1} , 50.0% of its potential was unused) and grasslands (158 t C ha^{-1} , 36.2% of its potential was unused). In contrast, forests and woodlands showed the smallest gap (79 t C ha^{-1} , 26.3% of its potential was unused), suggesting they are closer to their maximum capacity.

Two vegetation covers stood out for exceeding their potential carbon storage capacity: wetlands and marshes and riparian vegetation. Wetlands, despite having the lowest potential capacity ($C_p = 115 \text{ t C ha}^{-1}$), stored, on average, $C_s = 174 \text{ t C ha}^{-1}$, representing a surplus of +51.3%. Similarly, riparian vegetation exceeded its potential capacity, with a \hat{I} soc of 1.66. These exceptions are explained by the anaerobic conditions of these vegetation types, which slow the decomposition of organic matter, allowing carbon to accumulate and exceed the intrinsic capacity of the soil. However, this condition can be considered fragile because environmental changes, such as desiccation or drainage, could quickly reverse this accumulation, releasing carbon into the atmosphere. More details can be found in [Supplementary Table S5](#).

4 Discussion

4.1 Evaluating soil organic carbon storage capacity

In this study (Figure 4), we observed Al_a to be a reliable indicator of SOC stabilization in soils with $Al_a > 600 \text{ mg kg}^{-1}$, characteristic of volcanic soils or soils influenced by volcanic material (Rodríguez, 1993). In Chile, Matus et al. (2006) found that ammonium acetate (Al_a)-extractable aluminum better

correlated with SOC levels than the clay content in allophanic soils on a regional scale. Al_a reflects the formation of organo-Al complexes, which are key in SOC stabilization in acidic soils (Matus et al., 2008; Parada et al., 2024). In addition, the incomplete dispersion of the clay and silt fractions during textural analyses in volcanic soils makes it impossible to use the clay content as the sole indicator of C storage in these soils (Matus, 2021). On the contrary, in soils with lower Al_a contents, most likely dominated by less reactive crystalline clays, Al_a was not a reliable indicator of SOC stabilization. This suggests that the effectiveness of Al_a as an indicator depends on soil mineralogy and the predominant stabilization mechanism, which varies according to soil type (Kögel-Knabner and Amelung, 2021). In acidic soils, SOC stabilization occurs mainly through the formation of organic-Al complexes (Matus et al., 2008; Shimada et al., 2022), while in alkaline soils (common in northern Chile) other processes predominate.

In general terms, C saturation in soil results from the accumulation in different reservoirs (Six et al., 2002; Stewart et al., 2008), where chemical stabilization through interactions with mineral particles can be responsible for 72%–86% of the accumulated carbon (Matus et al., 2024; Begill et al., 2023). In this study, we aimed to replace the mineral particle-based indicator with a chemical index, such as Al_a , to assess the function in volcanic soils. By using quantile models and selecting the 95th percentile as a reference a broad concept of SOC saturation was adopted, integrating the contribution of all reservoirs in SOC stabilization and accumulation. From this perspective, the upper critical level, the 95th percentile (p95) should be interpreted as the threshold at which SOC accumulation ceases to be determined by edaphic properties and becomes influenced by environmental factors (Krull et al., 2003). This threshold represents a practical tool for land use management, since soils that exceed this level can be considered fragile due to the loss of their resilience to recover carbon that could eventually be lost in the face of anthropogenic interventions (Clunes et al., 2022b).

4.2 Carbon storage function in soils of the Aysén Region, Chile

The higher carbon storage potential observed in the Aysén Region (Figure 5), suggests a relatively high level of storage compared to other regions of the country and around the world. The values estimated in the Aysén Region exceeded those reported by Chen et al. (2019) for agricultural soils in France, who determined the maximum SOC content at various percentiles. These values ranged from 110 t ha⁻¹ to 260 t ha⁻¹ (0–50 cm). In comparison, 77.5% of the Aysén soils exceeded the maximum range found in France (C_p > 260 t ha⁻¹), with 46.3% of these doubling this maximum (C_p > 420 t ha⁻¹), and only 4.1% of the Aysén soils showing values below 110 t ha⁻¹. Although the differences in the depths considered in both studies could partially explain the variability in their estimates, carbon accumulation was not homogeneous throughout the profile and drastically decreased at greater depths, a phenomenon that was considered in the adjustments of our estimates (see Section 2.6).

It could be argued that this difference was generated because the evaluation in the Aysén Region included soils with diverse uses, not exclusively agricultural lands. However, 67.7% of the soils with C_p > 420 t ha⁻¹ corresponded to pastures, while no data from wetlands or swamps were observed in this C_p interval. On the contrary, 70.9% of the soils with C_p > 420 t ha⁻¹ had a Al_a > 600 mg kg⁻¹ (\bar{x} = 906.8 mg kg⁻¹), which could suggest that the mineralogy of the soils could explain this high storage capacity. Nonetheless, we recognize that there are other factors (e.g., soil water content) not considered in this study that could also have had an influence.

Regarding the current state of SOC storage, on average, the Aysén Region had a C_s = 238 t C ha⁻¹, a value exceeding the global averages. Minasny et al. (2017) collected global SOC data, with values ranging from 17.9 t C ha⁻¹ in Indonesian rice fields (0–15 cm) to 105.3 t C ha⁻¹ in New Zealand grasslands (0–30 cm). In contrast, Chilean volcanic soils, such as those in Aysén, tend to have higher values. Padarian et al. (2017) estimated stocks exceeding 100 t C ha⁻¹ between latitudes 43°S and 46°S, and Dube et al. (2012) reported stocks between 150 and 194 t C ha⁻¹ in silvopastoral Andisols (0–40 cm). Consistently, Muñoz et al. (2007) reported stocks of up to 136 t C ha⁻¹ in Alfisols of the Maule Region (0–40 cm), which further elevates the high carbon storage capacity of the Andisol soils of the Aysén Region.

Although SOC values in Aysén are high, the current state index (\bar{I} soc = 0.59) indicates that even with such high C_s values compared to national and international values, these soils still have the capacity to store more carbon. Therefore, effective land management considering the functional potential of soils could increase storage and promote carbon sequestration (Don et al., 2024), thus helping to mitigate the effects of climate change, as well as improving soil health.

Regarding the functionality indexes observed in the three classifications according to Al_a values, it was expected that the C_p values would increase with increasing Al_a values, that is, C_p would be lower in soils with Al_a < 200 mg kg⁻¹, higher in soils with Al_a between 200 and 600 mg kg⁻¹ and highest in soils with Al_a > 600 mg kg⁻¹ (ODEPA, 2024). However, this was not

fulfilled (Figure 5); the lowest average C_p was found in soils with Al_a between 200 and 600 mg kg⁻¹. At first, we assumed this could be due to differences in depth (mean value measure of group), but as it can be seen in Supplementary Table S3, no differences among varying soil depths with Al_a < 200 mg kg⁻¹ were found. We then observed that the bulk density values for these two groups was 0.85 g cm⁻³ for soils with Al_a < 200 mg kg⁻¹ and 0.54 g cm⁻³ for soils with Al_a between 200 and 600 mg kg⁻¹, which were less than expected based on the estimated mineralogy for each of the groups (> 1 g cm⁻³ in soils with Al_a < 200 mg kg⁻¹ and slightly less than 1 g cm⁻³ in soils with Al_a between 200 and 600 mg kg⁻¹). For this reason, we revised the variation of this variable by eliminating vegetation covers that, due to their genesis, had lower bulk density values, such as wetlands and marshes and riparian vegetation (< 0.5 g cm⁻³; Supplementary Material). However, this modification generated no differences in the C_p trend.

When analyzing the functionality indices of soils under different vegetation covers it has been assumed that certain ecosystems are large carbon sinks (Don et al., 2024), such as wetlands and swamps, nonetheless our estimates showed that these present the lowest C_p (Figure 6). This can be explained by organic soils low relative mineral content, which, according to the method proposed in this work, was expected to have a lower carbon storage potential in these soils. Nonetheless, this was not true in this case, in fact, wetlands and swamps were the only vegetation covers whose current state (C_s) exceeded their intrinsic potential (C_p) (Figure 6). This phenomenon is explained by the fact that the carbon accumulation in this type of ecosystem does not depend primarily on the soil matrix, but rather on its anaerobic condition, which slows the rate of decomposition. This allows the volume of plant litter input to be greater than the losses, generating accumulations that exceed the estimated levels.

As previously discussed, we consider that a condition where C_s > C_p represents a condition of fragility (Clunes et al., 2022b). Carbon that is accumulated above established levels can easily be lost if the ecosystem shifts from an anaerobic to an aerobic condition due to climate change, land-use changes, or other natural or anthropogenic processes. To exemplify the sensitivity and fragility of these ecosystems, Wang H. et al. (2022) modeled the effects of drought on wetlands in Georgia and South Carolina, United States, and found that the rate of SOC sequestration could decrease from 44% to 4% under recurrent drought conditions, which could represent a loss of 0.95 Tg C yr⁻¹ along the Atlantic Coast. Although the C_s of the rest of the analyzed vegetation covers did not exceed their potentials on average, some cases of forests and woodlands, grasslands and shrublands presented a current state index (\bar{I} soc) higher than 1. This could indicate recent changes in land use, where organic carbon has not yet reached an equilibrium, resulting in higher values than expected (Chen et al., 2019).

Soils with agricultural crops presented the highest carbon storage potential (C_p), surpassing even forests and woodlands. This finding is interesting, as it has traditionally been assumed that forests are the optimal carbon sinks. However, we argue that it is a mistake to evaluate soil carbon storage capacity based on vegetation cover. Forests are often considered as control treatments, but this capacity should be understood as an intrinsic property of the soil assessed through direct or indirect measurements using its dynamic and inherent properties. In

other words, although forests contribute more carbon to the soil than agricultural crops, as corroborated by our estimates (C_s forest > C_s agricultural crops), the exact amount of carbon stored is determined by the soil and its characteristics. In this sense, we identified that the soils with the greatest potential to store carbon are being used for agricultural crops, resulting in the largest gap between C_s and C_p , with -55.9% with respect to their potential. Improving management practices that favor residue accumulation could help reduce the gap between the current and potential states. It is also essential that more informed decision-making, a more efficient use of resources, and the sustainable use of natural resources are prioritized in agricultural lands in the Aysén Region in light of these results.

5 Conclusion

This work represents an initial proposal to quantify the ecosystem function of carbon accumulation in diverse soils on a regional scale, considering reactivity as the main mechanism. We recognize the constrictions of this approach, especially in soils with crystalline mineralogy and a more alkaline pH. Another limitation of this study is that it assumed that not all the C determined in a soil corresponded to C effectively stored by the soil, i.e., the study assumed that plant residues in degradation stabilized as residues themselves were not SOC, but were considered in the determination of C during extraction (e.g., determination of C in peatlands/wetlands). Therefore, these types of soils (e.g., soils under peatlands and wetlands) are extremely fragile because anthropogenic intervention can easily degrade them.

We propose evaluating new chemical indices or creating composite indices that reflect the variability of stabilization mechanisms found in Chilean soils. It is essential that future research further validate this proposal, explore alternative approaches, such as the parabolic curves discarded in this study, and determine whether the selected percentiles are sufficiently strict and accurate when estimating carbon accumulation potentials. This could aid us in the effective determination of saturation and allow us to detect areas of fragility for the carbon storage function.

The Aysén Region stands out in terms of its high soil carbon storage potential (C_p), with an average that exceeds 350 t C ha^{-1} (depth $\sim 8.5 \text{ dm}$), a very high level of storage compared to national and international values. Agricultural soils in the region, although they present the highest C_p , reflect the largest gap with respect to their current state (C_s), which confirms the necessity to improve management practices and carbon accumulation in these systems. This confirms that carbon storage should not be evaluated only in terms of the input of organic residues associated with vegetation cover, but in terms of the carbon storage capacity offered by the soils, determined by their inherent properties.

Wetland and swamp ecosystems were notable because they were the only vegetation covers where average C_s exceeded C_p , though this condition can be considered fragile because these systems are highly vulnerable to environmental changes. The possibility of rapid loss of accumulated carbon, especially under aerobic conditions, underscores the importance of their conservation as a key strategy in the face of climate change.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary Material](#), further inquiries can be directed to the corresponding author.

Author contributions

MF: Writing – original draft, Formal Analysis, Visualization, Methodology, Investigation, Writing – review and editing, Conceptualization, Data curation. DP: Supervision, Validation, Writing – review and editing, Conceptualization, Investigation. JC: Visualization, Supervision, Writing – review and editing. SV: Visualization, Writing – review and editing, Supervision.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2026.1789707/full#supplementary-material>

References

- Bagnall, D. K., Rieke, E. L., Morgan, C. L., Liptzin, D. L., Cappellazzi, S. B., and Honeycutt, C. W. (2023). A minimum suite of soil health indicators for North American agriculture. *Soil Secur.* 10, 100084. doi:10.1016/j.soisec.2023.100084
- Baveye, P. C., Baveye, J., and Gowdy, J. (2016). Soil “ecosystem” services and natural capital: critical appraisal of research on uncertain ground. *Front. Environ. Sci.* 4, 1–49. doi:10.3389/fenvs.2016.00041
- Begill, N., Don, A., and Poeplau, C. (2023). No detectable upper limit of mineral-associated organic carbon in temperate agricultural soils. *Glob. Chang. Biol.* 29 (16), 4662–4669. doi:10.1111/gcb.16804
- Casanova, M., Salazar, O., Seguel, O., and Luzio, W. (2013). “The soils of Chile,” in *World soil book series*. Dordrecht, Netherlands: Springer.
- Chen, S., Arrouays, D., Angers, D. A., Chenu, C., Barré, P., Martin, M. P., et al. (2019). National estimation of soil organic carbon storage potential for arable soils: a data-driven approach coupled with carbon-landscape zones. *Sci. Total Environ.* 666, 355–367. doi:10.1016/j.scitotenv.2019.02.249
- Clunes, J., and Pinochet, D. (2020). Leucine retention by the clay-sized mineral fraction. An indicator of C storage. *Agro Sur.* 48 (3), 37–46. doi:10.4206/agrosur.2020.v48n3-05
- Clunes, J., Dörner, J., Bravo, A., Jara, R., Zúñiga, F., Clunes, J., et al. (2022a). Did we underestimate silt and clay content in the textural analysis? *Chil. J. Agric. Anim. Sci.* 38 (1), 94–103. doi:10.29393/chjaas38-9dwj50009
- Clunes, J., Valle, S., Dörner, J., Martínez, O., Pinochet, D., Zúñiga, F., et al. (2022b). Soil fragility: a concept to ensure a sustainable use of soils. *Ecol. Indic.* 139, 108969. doi:10.1016/j.ecolind.2022.108969
- Cotrufo, M. F., and Lavelle, J. M. (2022). “Chapter one - soil organic matter formation, persistence, and functioning: a synthesis of current understanding to inform its conservation and regeneration,”. *Advances in agronomy*. Editor E. D. L. Sparks (Academic Press), 172, 1–66. doi:10.1016/bs.agron.2021.11.002
- Day, P. R. (1965). “Particle fractionation and particle-size analysis,” in *Methods of soil analysis: part 1*, Editor C. A. Black (Madison, Wisconsin, United States: American Society of Agronomy)
- Dominati, E., Patterson, M., and Mackay, A. (2010). A framework for classifying and quantifying the natural capital and ecosystem services of soils. *Ecol. Econ.* 69, 1858–1868. doi:10.1016/j.ecolecon.2010.05.002
- Don, A., Seidel, F., Leifeld, J., Kätterer, T., Martin, M., Pellerin, S., et al. (2024). Carbon sequestration in soils and climate change mitigation—Definitions and pitfalls. *Glob. Chang. Biol.* 30 (1), e16983. doi:10.1111/gcb.16983
- Dube, F., Espinosa, M., Stolpe, N. B., Zagal, E., Thevathasan, N. V., and Gordon, A. M. (2012). Productivity and carbon storage in silvopastoral systems with *Pinus ponderosa* and *Trifolium* spp., plantations and pasture on an Andisol in Patagonia, Chile. *Agrofor. Syst.* 86 (2), 113–128. doi:10.1007/s10457-011-9471-7
- European Commission (2006). *Proposal for a directive of the European Parliament and of the Council establishing a framework for the protection of soil and amending directive 2004/35/EC (COM(2006)232)*.
- Gunina, A., Smith, A. R., Kuz'yakov, Y., and Jones, D. L. (2017). Microbial uptake and utilization of low molecular weight organic substrates in soil depend on carbon oxidation state. *Biogeochemistry* 133 (1), 89–100. doi:10.1007/s10533-017-0313-1
- Hassink, J. (1997). The capacity of soils to preserve organic C and N by their association with clay and silt particles. *Plant Soil* 191 (1), 77–87. doi:10.1023/A:1004213929699
- Hepp, C. (2019). *Sistemas de Producción de Bovinos de Carne en la Patagonia Húmeda*. Instituto de Investigaciones Agropecuarias, Centro de Investigación INIA Tamel Aike, Coyhaique, Aysén-Patagonia, Chile.
- Hepp, C., and Stolpe, N. B. (2014). *Caracterización y propiedades de los suelos de la Patagonia occidental (Aysén)*. Coyhaique: Instituto de Investigaciones Agropecuarias, Centro de Investigación INIA Tamel Aike, 160. (Boletín INIA N° 298).
- Hoffland, E., Kuyper, T. W., Comans, R. N. J., and Creamer, R. E. (2020). Eco-functionality of organic matter in soils. *Plant Soil* 455 (1), 1–22. doi:10.1007/s11104-020-04651-9
- Jenkinson, D. S., Harkness, D. D., Vance, E. D., Adams, D. E., and Harrison, A. F. (1992). Calculating net primary production and annual input of organic matter to soil from the amount and radiocarbon content of soil organic matter. *Soil Biol. Biochem.* 24 (4), 295–308. doi:10.1016/0038-0717(92)90189-5
- Koenker, R. (2005). *Quantile regression*. Cambridge: Cambridge University Press.
- Kögel-Knabner, I., and Amelung, W. (2021). Soil organic matter in major pedogenic soil groups. *Geoderma* 384, 114785. doi:10.1016/j.geoderma.2020.114785
- Krull, E. S., Baldock, J. A., and Skjemstad, J. O. (2003). Importance of mechanisms and processes of the stabilisation of soil organic matter for modelling carbon turnover. *Funct. Plant Biol.* 30 (2), 207–222. doi:10.1071/fp02085
- López-Ulloa, M., Veldkamp, E., and de Koning, G. H. J. (2005). Soil carbon stabilization in converted tropical pastures and forests depends on soil type. *Soil Sci. Soc. Am. J.* 69 (4), 1110–1117. doi:10.2136/sssaj2004.0353
- Luzio, W. (2010). *Suelos de Chile*. Santiago, Chile: Universidad de Chile.
- Matus, F., Rumpel, C., Neculman, R., Panichini, M., and Mora, M. L. (2014). Soil carbon storage and stabilisation in andic soils: a review. *Catena* 120, 102–110. doi:10.1016/j.catena.2014.04.008
- Matus, F. J. (2021). Fine silt and clay content is the main factor defining maximal C and N accumulations in soils: a meta-analysis. *Sci. Rep.* 11 (1), 6438. doi:10.1038/s41598-021-84821-6
- Matus, F., Amigo, X., and Kristiansen, S. M. (2006). Aluminium stabilization controls organic carbon levels in Chilean volcanic soils. *Geoderma* 132 (1), 158–168. doi:10.1016/j.geoderma.2005.05.005
- Matus, F., Garrido, E., Sepúlveda, N., Cárcamo, I., Panichini, M., and Zagal, E. (2008). Relationship between extractable Al and organic C in volcanic soils of Chile. *Geoderma* 148 (2), 180–188. doi:10.1016/j.geoderma.2008.10.004
- Matus, F. J., Paz-Pellat, F., Covaleda, S., Etchevers, J. D., Hidalgo, C., and Báez, A. (2024). Upper limit of mineral-associated organic carbon in temperate and sub-tropical soils: how far is it? *Geoderma Reg.* 37, e00811. doi:10.1016/j.geoder.2024.e00811
- Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., et al. (2017). Soil carbon 4 per mille. *Geoderma* 292, 59–86. doi:10.1016/j.geoderma.2017.01.002
- Muñoz, C., Ovalle, C., and Zagal, E. (2007). Distribution of soil organic carbon stock in an Alfisol profile in Mediterranean Chilean ecosystems. *Rev. la Cienc. del Suelo Nutr. Vegetal* 7, 15–27.
- National Forestry Corporation (CONAF) (2020). Territorial information system. Available online at: <https://sit.conaf.cl/>.
- Oechel, W., Vourlitis, G., Hastings, S., Ault Jr., R. P., and Bryant, P. (1998). The effects of water table manipulation and elevated temperature on the net CO₂ flux of wet sedge tundra ecosystems. *Glob. Change Biol.* 4 (1), 77–90. doi:10.1046/j.1365-2486.1998.00110.x
- Oficina de Estudios y Políticas Agrarias (2021). *Informativo regional: Región de Aysén*.
- Oficina de Estudios y Políticas Agrarias (2024). Establecimiento de estándares y niveles mínimos técnicos para la medición de los parámetros físicos, químicos y biológicos de los suelos agropecuarios de Chile. (SIGESS) *Inf. Final.* 54.
- Padarian, J., Minasny, B., and McBratney, A. B. (2017). Chile and the Chilean soil grid: a contribution to GlobalSoilMap. *Geoderma Reg.* 9, 17–28. doi:10.1016/j.geoder.2016.12.001
- Parada, J., Neaman, A., Zamorano, D., Nájera, F., and Matus, F. (2024). Management and liming-induced changes in organo-Al/Fe complexes and amorphous mineral-associated organic carbon: implications for carbon sequestration in volcanic soils. *Soil Till. Res.* 242, 106133. doi:10.1016/j.still.2024.106133
- Percival, H. J., Parfitt, R. L., and Scott, N. A. (2000). Factors controlling soil carbon levels in New Zealand grasslands is clay content important? *Soil Sci. Soc. Am. J.* 64 (5), 1623–1630. doi:10.2136/sssaj2000.6451623x
- Rodríguez, J. (1993). *La fertilización de los cultivos: un método racional. Colección agrícola*. Editorial Pontificia Universidad Católica de Chile. 293.
- Ros, G., Hanegraaf, M., Hoffland, E., and van Riemsdijk, W. (2011). Predicting soil N mineralization: relevance of organic matter fractions and soil properties. *Soil Biol. Biochem.* 43 (8), 1714–1722. doi:10.1016/j.soilbio.2011.04.017
- Sadzawka, A., Carrasco, M., Grez, R., Mora, M., Flores, H., and Neaman, A. (2006). *Métodos de análisis recomendados para los suelos de Chile*. Santiago, Chile: Centro de Investigación Regional La Platina. 1–164.
- Shi, J., Song, M., Yang, L., Zhao, F., Wu, J., Li, J., et al. (2023). Recalcitrant organic carbon plays a key role in soil carbon sequestration along a long-term vegetation succession on the Loess Plateau. *Catena* 233, 107528. doi:10.1016/j.catena.2023.107528
- Shimada, H., Wagai, R., Inoue, Y., Tamura, K., and Asano, M. (2022). Millennium timescale carbon stability in an Andisol: how persistent are organo-metal complexes? *Geoderma* 417, 115820. doi:10.1016/j.geoderma.2022.115820
- Sistema de Incentivos para la Sustentabilidad Agroambiental de los Suelos Agropecuarios (SIRSD) (2004). Soil data from the soil recovery program (unpublished dataset). Chile.
- Six, J., Conant, R. T., Paul, E. A., and Paustian, K. (2002). Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. *Plant Soil* 241, 155–176. doi:10.1023/a:1016125726789
- Stewart, C. E., Plante, A. F., Paustian, K., Conant, R. T., and Six, J. (2008). Soil carbon saturation: linking concept and measurable carbon pools. *Soil Sci. Soc. Am. J.* 72 (2), 379–392. doi:10.2136/sssaj2007.0104
- Stolpe, N. B., and Hepp, C. (2014). Caracterización taxonómica de los suelos de los valles de interés agropecuario de la Región de Aysén (Patagonia Occidental-Chile). Coyhaique: Instituto de Investigaciones Agropecuarias, Centro de Investigación INIA Tamel Aike. 168. (Boletín INIA N° 199).
- Valle, S. R., Carrasco, J., Pinochet, D., Soto, P., and Mac Donald, R. (2015). Spatial distribution assessment of extractable Al, (NaF) pH and phosphate retention as tests to differentiate among volcanic soils. *Catena* 127, 17–25. doi:10.1016/j.catena.2014.12.011

- Vogel, H.-J., Eberhardt, E., Franko, U., Lang, B., Ließ, M., Weller, U., et al. (2019). Quantitative evaluation of soil functions: potential and state. *Front. Environ. Sci.* 7, 164. doi:10.3389/fenvs.2019.00164
- von Lützw, M., Kögel-Knabner, I., Ludwig, B., Matzner, E., Flessa, H., Ekschmitt, K., et al. (2008). Stabilization mechanisms of organic matter in four temperate soils: development and application of a conceptual model. *J. Plant Nutr. Soil Sci.* 171 (1), 111–124. doi:10.1002/jpln.200700047
- Wang, C., Pan, Y., Zhang, Z., Xiao, R., and Zhang, M. (2022). Effect of straw decomposition on organic carbon fractions and aggregate stability in salt marshes. *Sci. Total Environ.* 777, 145852. doi:10.1016/j.scitotenv.2021.145852
- Wang, H., Dai, Z., Trettin, C. C., Krauss, K. W., Noe, G. B., Burton, A. J., et al. (2022). Modeling impacts of drought-induced salinity intrusion on carbon dynamics in tidal freshwater forested wetlands. *Ecol. Appl.* 32 (8), e2700. doi:10.1002/eap.2700
- Wickland, K., Striegl, R., Mast, M., and Clow, D. (2001). Carbon gas exchange at a southern Rocky Mountain wetland, 1996–1998. *Glob. Biogeochem. Cycles.* 15, 321–335. doi:10.1029/2000GB001325
- Wiesmeier, M., Urbanski, L., Hobley, E., Lang, B., von Lützw, M., Marin-Spiotta, E., et al. (2019). Soil organic carbon storage as a key function of soils—A review of drivers and indicators at various scales. *Geoderma* 333, 149–162. doi:10.1016/j.geoderma.2018.07.026
- Yudina, A., and Kuzyakov, Y. (2023). Dual nature of soil structure: the unity of aggregates and pores. *Geoderma* 434, 116478. doi:10.1016/j.geoderma.2023.116478
- Zunino, H., Borie, F., Aguilera, S., Martin, J. P., and Haider, K. (1982). Decomposition of ¹⁴C-labeled glucose, plant and microbial products and phenols in volcanic ash-derived soils of Chile. *Soil Biol. Biochem.* 14 (1), 37–43. doi:10.1016/0038-0717(82)90074-8