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Assessment of Carbon and Water Stored in the Soil of a Bofedal in the Community of Cullhuay in the Central Andes of Peru.

Evaluación del carbono y del agua almacenados en el suelo de un bofedal de la comunidad de Cullhuay, en los Andes centrales del Perú

Rosycela Valerio[1], Diana Ayala Mena[1], Mónica Maldonado-Fonkén[2], Damaso W. Ramírez[1]

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Highlights:

1. The Cullhuay bofedal stores an estimated 957.69 t C within the upper 30 cm of soil.
2. Water storage was estimated at 96,347.11 m³ over an assumed soil depth of 2 m.
3. Soil organic carbon and volumetric water content showed a moderate positive correlation (Spearman's $\rho = 0.6705$).

1. Universidad Científica del Sur, Facultad de Ciencias Ambientales, Lima, Perú. Corresponding author: 180000890@cientifica.edu.pe
2. División de Ecología Vegetal, Centro de Ornitología y Biodiversidad (CORBIDI), Santiago de Surco, Lima, Perú.

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ABSTRACT

Introduction. High Andean wetlands (*bofedales*) are important ecosystems for carbon and water storage in the upper reaches of river basins. However, they are threatened by anthropogenic activities, including infrastructure development, water diversion, mining, peat extraction, and overgrazing, as well as by climate change. **Objective.** To assess carbon and water storage in the soil of a *bofedal* in the community of Cullhuay, in the Andes of Lima, Peru. **Materials and Methods.** Soil organic carbon (SOC) stock was estimated in the upper 30 cm of soil, and water storage was estimated for an assumed depth of 2 m. Forty-five sampling points were randomly selected across three zones (dry, wet, and saturated). Soil bulk density was determined using the known-volume cylinder method, while carbon content was estimated from organic matter measured by loss on ignition using the Van Bemmelen conversion factor. Gravimetric and volumetric water contents were calculated from field-moist soil samples. **Results.** Total SOC stock was estimated at 957.69 t C across 6.83 ha (140.22 t C/ha), while estimated water storage was 96,347.11 m³. The saturated zone had the highest total SOC stock (354.02 t C), whereas the wet zone had the highest estimated water storage (39,468.51 m³). SOC stock and volumetric water content showed a moderate positive correlation (Spearman's $\rho = 0.6705$). **Conclusions.** Soil organic carbon stock and volumetric water content were positively associated in the Cullhuay *bofedal*. These findings highlight the importance of this ecosystem for carbon and water storage and support the need for its conservation and appropriate management.

Keywords: Water storage; peatlands; carbon storage; bofedales; high Andean wetlands.

RESUMEN

Introducción. Los humedales altoandinos (bofedales) son ecosistemas importantes para el almacenamiento de carbono y agua en las cabeceras de las cuencas hidrográficas. Sin embargo, están amenazados por la construcción de infraestructura, el desvío de agua, la minería, la extracción de turba, el sobrepastoreo y el cambio climático. **Objetivo.** Evaluar el almacenamiento de carbono y agua en el suelo de un bofedal de la comunidad de Cullhuay, en los Andes de Lima, Perú. **Materiales y métodos.** Se estimó el carbono orgánico del suelo (COS) en los primeros 30 cm y el almacenamiento de agua considerando una profundidad supuesta de 2 m. Se seleccionaron aleatoriamente 45 puntos de muestreo en tres zonas: seca, húmeda y saturada. La densidad aparente se determinó mediante cilindros de volumen conocido y el carbono se estimó a partir de la materia orgánica cuantificada por pérdida por ignición, utilizando el factor de Van Bemmelen. Los contenidos gravimétrico y volumétrico de agua se calcularon a partir de muestras con humedad de campo. **Resultados.** Se estimaron 957,69 t C en 6,83 ha (140,22 t C/ha) y 96.347,11 m³ de agua. La zona saturada presentó la mayor reserva total de carbono (354,02 t C) y la húmeda, el mayor volumen estimado de agua (39.468,51 m³). Se observó una correlación positiva moderada entre carbono y contenido volumétrico de agua (ρ de Spearman = 0,6705). **Conclusiones.** El carbono orgánico y el contenido volumétrico de agua presentaron una asociación positiva en Cullhuay, destacando la importancia de conservar y gestionar adecuadamente este ecosistema.

Palabras clave: Almacenamiento de agua; turberas; almacenamiento de carbono; bofedales; humedales altoandinos.

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INTRODUCTION

Bofedales are high Andean hydromorphic ecosystems (a type of wetland) characterized by herbaceous vegetation and potentially deep organic soils (peat). In the Andean region, they are known by different names, such as peat bogs, oconales, vegas, and mallines [1-3]. These ecosystems provide water recharge and flow regulation services. They act as carbon sinks and contribute to flood mitigation, soil nutrient cycling, and climate regulation [4-8]. Carbon storage occurs when the accumulation of organic matter exceeds its rate of decomposition (9), while carbon capture occurs in plants through the fixation of atmospheric CO_2 [10-11]. Water storage occurs through the infiltration of precipitation, including rain, hail, and snow, into wetland soils. Once saturated, these soils can gradually release stored water to lower areas. This characteristic helps maintain forage availability during periods of low water availability and supports livestock activities [12]. It also contributes to the hydrological cycle through water provision, regulation, and aquifer recharge in the upper parts of watersheds [13]. Both services are related, as water saturation can create conditions that slow organic matter decomposition and favor carbon retention [14].

In Peru, bofedales cover approximately 1% (1,052,210.6 ha) of the country's territory [15]. Despite their limited extent, they play an important role in climate change mitigation. However, they are threatened by anthropogenic activities, including overgrazing, mining, infrastructure development, and peat extraction [16-19].

The Cullhuay bofedal supplies water to streams serving downstream settlements, including the community of Cullhuay, which has a population of 286 inhabitants [20]. It is located within the Chillón River basin, the second-largest basin supplying water to Lima, the country's most populous city [21]. However, its carbon and water storage remain poorly characterized. Furthermore, information on carbon storage in bofedales remains limited, despite the relevance of these ecosystems to national climate change adaptation efforts. In this context, this study aimed to estimate the amount of carbon and the volume of water stored in the soil of the Cullhuay bofedal, in the Andes of Lima.

MATERIALS AND METHODS

Study area. The study was conducted in the Cullhuay *bofedal* (6.83 ha), located at an elevation of 4,400 m above sea level in the upper Chillón River basin (coordinates: 340,876.31 m E and 8,743,730.34 m S; Zone 18L), near the community of Cullhuay. The study area is located in the district of Huaros, province of Canta, department of Lima **(Figure 1)**. The main economic activities of the local population are agriculture and livestock farming, including the raising of cattle, sheep, and alpacas. The area has two distinct seasons: a wet season from December to April and a dry season from May to November. Average annual precipitation ranges from 350 to 900 mm [22].

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Sampling design. Sampling was conducted in July 2023. Stratified random sampling was used for both soil carbon and water storage analyses. Three strata, hereafter referred to as zones, were defined according to soil moisture conditions and vegetation cover: *i)* saturated zone, characterized by surface water or standing water, living vegetation, and water splashing when pressure was applied to the soil during walking; *ii)* wet zone, characterized by living vegetation and moist soil that did not produce splashing during walking but was perceptibly wet to the touch; and *iii)* dry zone, characterized by the absence of visible soil moisture and sparse vegetation cover. The stratification was based on previous studies of moisture gradients in *bofedales* [23] and the methodological guidelines of the Peruvian Ministry of Environment [24]. Satellite images from Google Earth were used to delineate the wetland area. The delineated area was then transferred to ArcGIS, where a 5 × 5 m grid was superimposed on each zone. A 1 × 1 m grid was positioned at the center of each grid cell, with the remaining area serving as a buffer zone. Sampling points were randomly selected using the random function in Excel, with 15 sampling points per zone, resulting in a total of 45 points across the study area (**Figure 1**).

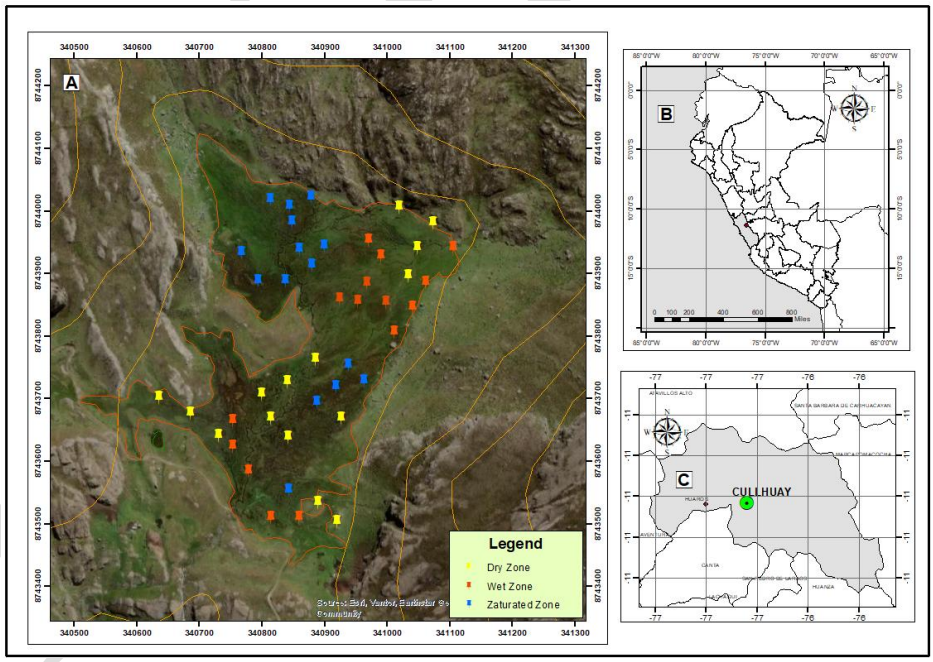


Figure 1. (A) Distribution of sampling points by zone (dry, wet, and saturated) and (B, C) location of the Cullhuay *bofedal*.

Soil organic carbon. Soil organic carbon (SOC) was estimated based on soil bulk density, organic matter content (%OM), carbon content (%C), and sampling depth (P = 30 cm) (25). Soil organic matter content was estimated using the loss-on-ignition (LOI) method described by Schulte EE, Hopkins BG (26). Soil samples were collected from the upper 30 cm using a soil auger (diameter = 4 cm). Each sample was stored in a sealed, labeled, airtight bag. Samples were oven-dried at 105 °C for 24 hours to obtain their initial dry mass (P1), followed by ignition at 360 °C for 2 hours to determine the residual mass (P2)**.** The percentage of organic matter was calculated using the following equation:

$$\%OM = [(P1 - P2) / P1] \times 100$$

where %OM is the organic matter percentage, P1 (g) is the initial dry sample mass, and P2 (g) is the sample mass after ignition.

The organic matter percentage was converted to estimated soil organic carbon percentage (%C) using the conventional Van Bemmelen conversion factor of 1.724, which assumes that carbon accounts for approximately 58% of soil organic matter [27-28]:

$$\%C = \%OM / 1.724$$

Soil bulk density was determined using the known-volume cylinder method (diameter = 4 inches; height = 10 cm) (29). The metal cylinder was inserted into the soil to a depth of 10 cm from the surface (24). Bulk density was calculated using the following equation 2:

$$Da = Ms / V$$

where Da (g/cm³) is soil bulk density, Ms (g) is dry soil mass, and V (cm³) is the cylinder volume.

Soil organic carbon stock per unit area was calculated based on soil carbon percentage, bulk density, and sampling depth [25]:

$$SOC = \%C \times P \times Da$$

where SOC (t C/ha) is soil organic carbon stock per hectare, %C is the numerical percentage of carbon, P (cm) is sampling depth, and Da (g/cm³) is soil bulk density.

The total soil organic carbon stock for each zone was estimated by multiplying the corresponding stock per hectare by the area of that zone:

$$SOCtotal = SOC \times A$$

where SOCtotal (t C) is the total soil organic carbon stock and A (ha) is the area of the corresponding zone.

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Potential volume of stored water. Soil samples for estimating water storage were collected from the three previously defined zones (wet, saturated, and dry) using a cylinder of known volume (diameter = 4 inches; height = 10 cm). The cylinder was inserted into the soil to a depth of 10 cm from the surface [24]. The samples were weighed before drying and stored in a cooler at 4 °C during transport to the Laboratory of Chemistry and Biochemistry of Natural Products at the Scientific University of the South. In the laboratory, samples were oven-dried at 105 °C for 24 hours to determine their dry mass [30].

Gravimetric water content was calculated from the difference between wet and dry soil mass:

$$Wg\ (\%) = [(Mh - Ms) / Ms] \times 100$$

where Wg (%) is gravimetric water content, Mh (g) is wet soil mass, and Ms (g) is dry soil mass.

Volumetric water content was calculated from gravimetric water content and soil bulk density:

$$\theta\ (\%) = Wg\ (\%) \times (Da / \rho w)$$

where θ (%) is volumetric water content, Wg (%) is gravimetric water content, Da (g/cm³) is soil bulk density, and ρw (g/cm³) is water density, approximated as 1 g/cm³.

The estimated volume of stored water was calculated following the methodology described in reference [31]. To standardize the calculation, a soil depth of 2 m was assumed, and the volumetric water content measured in the collected samples was extrapolated to this depth:

$$PVSW = A \times P \times (\theta / 100)$$

where PVSW (m³) is the estimated volume of stored water, A (m²) is the area of the corresponding zone, P (m) is the assumed soil depth (2 m), and θ (%) is volumetric water content.

The volumetric water content was determined from soil samples collected under field moisture conditions, without laboratory saturation. Therefore, the estimated water volume represents water stored under the moisture conditions observed at the time of sampling, extrapolated to an assumed soil depth of 2 m, rather than the maximum water storage capacity of the *bofedal*.

Statistical analysis. Soil carbon percentage, bulk density, and volumetric water content were summarized using descriptive statistics and expressed as mean and standard deviation. Differences among the three zones (saturated,

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wet, and dry) of the Cullhuay *bofedal* were evaluated using the nonparametric Kruskal–Wallis test. Pairwise comparisons among zones were performed using Dunn's post hoc test, with statistical significance set at $p < 0.05$. Statistical analyses and graphs were generated using PAST 4.13 and Excel. The relationship between soil organic carbon stock and volumetric water content across the three zones was evaluated using Spearman's rank correlation coefficient (ϱ). Excel and PAST 4.13 were used to generate the scatterplot and linear trend line and to perform the Spearman correlation analysis.

RESULTS

Based on soil samples collected throughout the *bofedal*, the total soil organic carbon (SOC) stock was estimated at 957.69 t C across 6.83 ha, equivalent to an average of 140.22 t C/ha. SOC stock per unit area and soil carbon percentage (%C) were higher in the saturated zone than in the other zones (Table 1). Mean soil bulk density (Da) was 0.17 g/cm³, with the highest value recorded in the dry zone **(Table 1)**. Greater variability in SOC was observed in the saturated zone. Pairwise comparisons of SOC, %C, and Da showed significant differences between the dry zone and both the wet and saturated zones ($p < 0.05$), whereas no significant differences were observed between the wet and saturated zones **(Figures 2a–c)**. The estimated volume of water stored in the *bofedal* was 96,347.11 m³ across 6.83 ha, equivalent to 14,106.46 m³/ha. This estimate was based on the volumetric water content measured under field moisture conditions and extrapolated to an assumed soil depth of 2 m. The wet zone had the highest estimated total volume of stored water (PVSW), whereas the saturated zone exhibited the highest volumetric water content (θ) **(Table 1)**. Pairwise comparisons of volumetric water content showed significant differences among all three zones ($p < 0.05$; **Figure 2d**).

Table 1. Soil organic carbon stock, soil carbon percentage, bulk density, volumetric water content, and estimated water storage in the three zones of the Cullhuay *bofedal*.

Zone	A (ha)	P (cm)	n	C (%)	Da (g/cm³)	θ (%)	PVSW (m³)	Total SOC (t C)
Dry	2.563	30	15	16	0.21	37	19,013.45	265.53
Wet	2.305	30	15	35	0.14	86	39,468.51	338.13
Saturated	1.959	30	15	38	0.16	97	37,865.15	354.02

A = area; **P** = sampling depth for SOC determination; **n** = number of samples; *C* = soil carbon percentage; **Da** = soil bulk density; **θ** = volumetric water content; **PVSW** = estimated volume of stored water; **SOC** = soil organic carbon stock. Water storage was estimated assuming a soil depth of 2 m. The carbon values in the final column represent the total stock estimated for each zone.

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Table 2. Comparison of soil organic carbon stocks, soil carbon percentages, and bulk density reported for the Cullhuay *bofedal* and other Andean wetlands.

Study location	Soil depth (cm)	SOC (t C/ha)	C (%)	Da (g/cm³)	Source
Cullhuay–Huaros, Peru	0–30	140.22	30	0.17	Present study
Chalhuanca–Arequipa, Peru	0–30	218.28	43.1	—	Alvis-Ccoropuna et al. (2021)
Churia–Ayacucho, Peru	0–60	330.16	5.92	0.937	Omonte (2022)
Chaqirayoq–Ayacucho, Peru	0–60	343.18	7.21	0.823	Omonte (2022)
Pantiumpampa–Ayacucho, Peru	0–60	959.15	24.40	0.657	Omonte (2022)
Junín, Peru	0–30	66.43	1.55	1.429	Chang and Mandarachi (2021)
Arequipa, Peru — Bofedal No. 5	0–80	77	—	—	León Tinoco (2016)
Arequipa, Peru — Bofedal No. 6	0–70	47	—	—	León Tinoco (2016)
Manasaya, Bolivia	Variable*	1,040	23.9	0.17	Hribljan et al. (2015)
Chimborazo, Ecuador	0–100	164.17	4.22	0.65	Lozano Rodríguez (2017)

SOC = soil organic carbon stock; **C** = soil carbon percentage; Da = soil bulk density. Values are reported as published in the original studies or, where indicated, as arithmetic means calculated from the reported soil layers. Sampling depths, soil characteristics, and analytical methods differ among studies; therefore, these values are intended for descriptive comparison and should not be interpreted as directly equivalent estimates. The Manasaya carbon stock represents a basin-scale estimate based on variable peat thickness, with a mean thickness of approximately 4.7 m and a maximum estimated thickness of 7–10 m. A dash (—) indicates that a representative value was not established for the corresponding study.

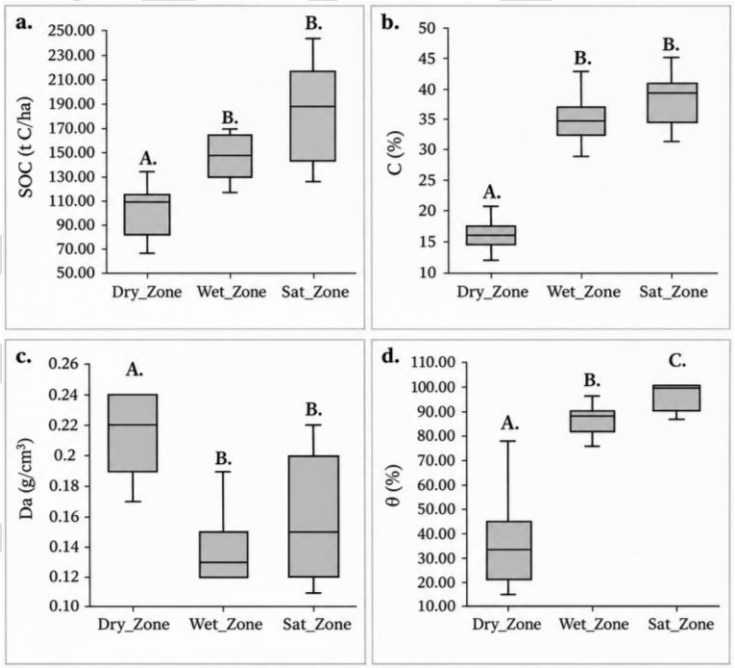


Figure 2. Distribution of (a) soil organic carbon stock (t C/ha), (b) soil carbon percentage (%), (c) soil bulk density (g/cm³), and (d) volumetric water content (%) across the dry, wet, and saturated zones of the Cullhuay *bofedal***.** Boxes represent the interquartile range (middle 50% of the data), with horizontal lines indicating the median. Different letters indicate statistically significant differences among zones based on the Kruskal–Wallis test followed by Dunn's post hoc test for pairwise comparisons ($p < 0.05$).

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Relationship between soil organic carbon and water content. A moderate positive correlation was observed between soil organic carbon stock and volumetric water content (Spearman's $\rho = 0.6705$), indicating that higher soil water content was generally associated with greater carbon storage. As shown in **Figure 3**, the wet and saturated zones exhibited higher soil organic carbon stocks and volumetric water content than the dry zone.

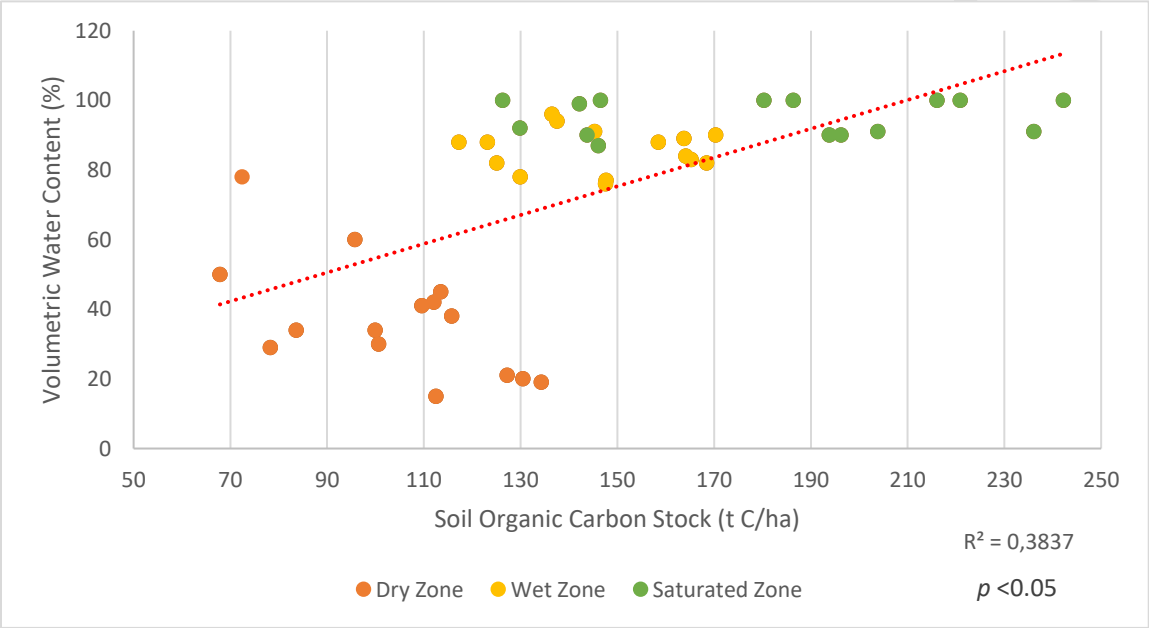


Figure 3. Relationship between soil organic carbon stock (t C/ha) and volumetric water content (%) in the dry, wet, and saturated zones of the Cullhuay *bofedal*. The dotted line represents the linear regression trend ($R^2 = 0.3837$). A moderate positive correlation was observed (Spearman's $\rho = 0.6705$; $p < 0.05$).

DISCUSSION

The soil organic carbon stocks and carbon percentages obtained in this study fall within the broad range of values reported for Andean wetlands (**Table 2**) [23, 32-38]. However, comparisons among studies should be interpreted cautiously because sampling depths, soil characteristics, analytical methods, and dominant vegetation differ across sites [32, 39-40]. Organic carbon accumulation varies among plant species and can be particularly high in cushion-forming plants [41]. Although cushion plants, such as *Distichia muscoides*, were observed in the Cullhuay *bofedal*, this species was not dominant. Additionally, the use of a conventional conversion factor to estimate organic carbon from soil organic matter may introduce some uncertainty, as this relationship can vary with soil characteristics [27-28].

Another factor that may influence carbon storage is wetland hydrology, particularly in wet and saturated areas, where prolonged water saturation can create anaerobic conditions that favor carbon accumulation by slowing organic matter decomposition [33,42]. Accordingly, higher soil water content may promote organic matter accumulation by limiting aerobic decomposition under oxygen-deficient conditions [42-43]. Previous research has also shown that organic matter decomposition is generally slower in wetland soils than in dryland soils [38]. This mechanism is consistent with the higher carbon stocks observed in the saturated zone compared with the dry zone in the present study.

The dry zone exhibited lower soil organic carbon stocks and carbon percentages, potentially associated with lower water availability. This zone also had sparse vegetation cover and more compacted soil, possibly reflecting the effects of grazing by sheep and horses. Previous research in a desert steppe in Inner Mongolia reported a 12.8% reduction in soil organic carbon within the upper 30 cm under heavy grazing, associated with reduced aboveground biomass [44]. Similarly, lower carbon contents have been reported in disturbed wetlands compared with relatively undisturbed areas [45-46]. Continued disturbance of the Cullhuay *bofedal* could therefore compromise the ecosystem services it provides.

Drainage through a canal toward the lower part of the community may also affect water and carbon storage in the dry zone. Given the moderate slope, drainage may reduce water availability along the wetland margins, potentially increasing soil aeration, organic matter decomposition, and CO_2 emissions [45,64]. Soil organic carbon distribution can also vary with environmental conditions and soil depth [47]. As shown in **Figure 1**, 46% of the sampling points in the dry zone were located near drainage channels, where the lowest recorded values of soil organic carbon (67.85 t C/ha) and volumetric water content (15%) were observed. In the saturated zone, a shallow layer of water was observed covering the soil surface, suggesting conditions that may limit oxygen availability and slow organic matter decomposition. Reduced oxygen availability can restrict aerobic microbial decomposition, favoring carbon accumulation. Vegetation growing under these conditions may also contribute to carbon fixation through photosynthesis [48].

Soil bulk density. The bulk density values obtained in this study fall within the ranges previously reported for Andean wetland soils (**Table 2**) [33, 49-50]. Lower bulk density and greater peat depth have been associated with greater water and carbon storage capacity in bofedales [24]. Soil organic matter also influences bulk density by promoting soil aggregation and reducing the density of the soil matrix [51].

In the Cullhuay *bofedal*, roots were observed within the upper 30 cm of soil, which may influence bulk density, as reported in a study conducted in Chimborazo, Ecuador [46]. Similarly, previous research has shown that soils containing

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substantial amounts of organic matter and moisture near the surface tend to exhibit lower bulk density [52]. These factors may help explain the relatively low bulk density values observed in the study area.

Potential volume of stored water. The estimated volume of water stored in the Cullhuay *bofedal* highlights its potential importance for local water storage and regulation. Water availability may also favor the establishment of vegetation associated with carbon accumulation and peat formation [41]. Previous research has indicated that bofedales can contribute up to 74% of total water flow during the dry season [53]. Their hydrological dynamics are influenced by climatic conditions and associated changes in water availability [54]. In bofedales located in the headwaters of the Chillón River basin (Lima), an average potential water storage volume of 13.45 million m^3 was estimated for the period 1986–2015, assuming a uniform depth of 2 m [31].

The saturated zone in the present study exhibited a high volumetric water content (97%). A comparable value of 97.4% was reported at a sampling point in the Aynacha Pacoco *bofedal* in Bolivia [43]. In contrast, lower volumetric water content was recorded in the dry zone. This difference may be associated with the location of sampling sites along the wetland margins, where grazing by sheep and horses and water management practices may affect soil conditions. Grazing-related soil compaction can alter soil physical properties and water storage dynamics [55].

Sampling conditions may also influence soil moisture measurements, particularly in areas exposed to solar radiation and with limited vegetation cover, where evaporation may be greater [56]. Furthermore, climate change-related reductions in water availability during certain periods may particularly affect vegetation along wetland margins, where access to surface water or groundwater can be more limited [40, 57-58].

The wet and saturated zones exhibited characteristics associated with a relatively preserved *bofedal*, including substantial vegetation cover. Vegetation can influence soil water storage [59], and in these zones, plants were observed to be vigorous, with extensive cover and roots extending beyond 30 cm. Soil organic matter may contribute to water retention by influencing pore structure and facilitating capillary water movement [40,30]. Higher organic matter content can also influence soil porosity and water retention capacity [43]. Under saturated conditions, limited oxygen availability may reduce organic matter decomposition and favor carbon accumulation [30, 35], consistent with the higher carbon stocks observed in the wet and saturated zones. Previous studies have associated high water storage values with soil profile characteristics and precipitation patterns [33]. Precipitation dynamics were not evaluated in the present study and should be considered in future research.

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Relationship between soil organic carbon and volumetric water content. Previous studies have reported associations between soil organic carbon and water content, as soil organic matter influences soil structure, pore distribution, and water infiltration [60], while hydrological conditions can affect organic carbon accumulation and microbial activity [61-62]. In the present study, a moderate positive correlation was observed between soil organic carbon stock and volumetric water content (**Figure 3**), indicating that higher water content was generally associated with greater carbon storage.

Water availability may influence carbon accumulation because saturated conditions can favor organic matter preservation [62]. Conversely, lower carbon stocks were observed in the dry zone. This pattern may be associated with greater exposure of surface soil layers to environmental and anthropogenic disturbances, which can affect carbon retention [63]. Previous research in Andean peatlands has shown that drainage can alter carbon cycling and increase the likelihood of these ecosystems becoming carbon sources rather than sinks [64].

The relationship between soil organic carbon and water retention is also influenced by soil texture [65]. In the Cullhuay *bofedal*, grazing and water extraction by local residents may additionally affect soil physical conditions and water availability.

The degradation of the Cullhuay *bofedal* could affect surrounding communities that depend on its water resources for crop irrigation, domestic use, and livestock, during both wet and dry periods. Changes in water storage and regulation could also affect the wetland's contribution to the Chillón River basin, potentially reducing downstream water availability. Furthermore, degradation and drainage may promote the decomposition of previously accumulated organic matter and increase carbon emissions, potentially reducing the ecosystem's contribution to climate change mitigation. These potential consequences highlight the importance of conserving and managing the Cullhuay *bofedal* to maintain its ecological functions and the services it provides to local communities.

CONCLUSIONS

The Cullhuay *bofedal* was estimated to store 957.69 t C within the upper 30 cm of soil and 96,347.11 m³ of water over an assumed soil depth of 2 m, based on volumetric water content measured under field moisture conditions. The wet and saturated zones did not differ significantly in soil organic carbon variables but showed significant differences in volumetric water content. In contrast, the dry zone exhibited significantly lower soil organic carbon stocks and volumetric water content than the other zones. Soil bulk density was also higher in the dry zone than in the wet and saturated zones. A moderate positive correlation was observed between soil organic carbon stock and volumetric

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water content, suggesting an association between soil moisture conditions and carbon storage. These findings highlight the importance of bofedales for carbon and water storage and support the need for their conservation and appropriate management. The involvement of local and regional stakeholders is essential to promoting the long-term conservation and sustainable use of these ecosystems. Future research should include a detailed assessment of slope and microrelief to better understand their influence on water distribution and carbon storage.

ETHICAL CONSIDERATIONS

The research was conducted in accordance with established ethical principles for scientific research and applicable SERFOR regulations, under authorization No. D000201-2023-MIDAGRI-SERFOR-ATFFS and with the approval of the Institutional Ethics Committee, as documented in Certificate No. 034-CIEI-AB-Científica-2022. Information and contributions provided by participants were used exclusively for academic purposes. Permission was also obtained from the Cullhuay community, with respect for its norms, customs, and collective rights.

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DECLARATION OF COMPETING INTEREST

The authors declare no competing interests.

AUTHOR CONTRIBUTIONS

Ariza Valerio R.: Conceptualization, investigation, formal analysis, and writing – original draft. **Ayala Mena D.:** Conceptualization, investigation, formal analysis, and writing – original draft. **Maldonado Fonkén M. S.:** Formal analysis and writing – review and editing. **Ramírez D. W.:** Formal analysis and writing – review and editing.

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