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Changes in the Soil Organic Carbon of Grasslands in the High Andes of Peru after Their Conversion to Croplands and Their Environmental Controls

Paolo Rivaldo Medina Quispe [1], Marco Aurelio Arizapana-Almonacid [1] and Marcelo Daniel Nosetto [2,3,*]

[1] Grupo de Investigación en Sensoramiento Remoto y Ecología de Montaña, Escuela Profesional de Ingeniería y Gestión Ambiental, Universidad Nacional Autónoma de Huanta, Jr. Razuhuillca, 624, Huanta 0512, Peru; paolomedina2017@gmail.com (P.R.M.Q.); marizapana@gmail.com (M.A.A.-A.)
[2] Grupo de Estudios Ambientales, Instituto de Matemática Aplicada San Luis (UNSL & CONICET), Av. Ejército de los Andes 950, San Luis 5700, Argentina
[3] Cátedra de Climatología Agrícola, Facultad de Ciencias Agropecuarias (UNER), Ruta 11, km 10, Oro Verde 3100, Argentina
* Correspondence: marcelo.nosetto@uner.edu.ar

Abstract: The high-Andean grasslands of Peru provide a wide range of goods and services, not only locally, but also regionally and globally. However, land-use change and global warming are threatening these ecosystems, of which soil organic carbon (SOC) is a key element affecting their sustainability. In this study, we have analyzed the variation of SOC stocks to a depth of 20 cm in 16 paired cropland and grassland sites located in the Sullccapallcca stream micro-watershed (elevation > 3600 m.a.s.l., Ayacucho, Peru). We have also analyzed the environmental controls on the SOC stocks and their variation with land-use change. We found that the studied high-Andean grasslands store high SOC contents (247 Tn SOC ha^{-1}), whose spatial variability was partially explained by the slope of the terrain ($r^2 = 0.26$, $p < 0.05$). Despite the higher NDVI, the conversion of these grasslands into croplands decreased the SOC stock by 39 Tn SOC ha^{-1} on average, a decrease that was more pronounced when the initial SOC content of the grassland was higher ($r^2 = 0.60$, $p < 0.05$). This study provides the first evidence of the effects of land-use change on the SOC in the region, although the mechanisms involved still need to be investigated.

Keywords: land-use change; NDVI; aboveground primary productivity; SOC

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1. Introduction

The high-Andean grasslands of South America are important ecosystems because they support the livelihoods of many people who base their economies and development on the many goods and services that they provide. These ecosystems are also affected by climate change and the expansion of the agricultural frontier [1], largely due to growing local and global demand for food. In fact, the region has a medium-to-high conservation priority due to its vulnerability to rapid anthropogenic disturbances [2,3]. In turn, land-use change can lead to losses in agricultural productivity, affecting the livelihoods and vulnerabilities of families in the region [4]. The Huanta province in the department of Ayacucho (Peru) is not exempt from this trend, where the conversion of native grasslands to croplands can have negative impacts on ecosystem services [5]. For example, between 2000 and 2010, the agricultural area increased almost threefold in the region, mainly at the expense of the area with native vegetation [6]. In particular, soil organic carbon (SOC) is a key element of these ecosystems, as it contributes to several ecological processes, such as the following: soil water dynamics, nutrient storage, and the regulation of climatological processes, among others [7,8]. In this sense, in this paper, we study the variation of SOC stocks in cropland soils in the high-Andean systems of Peru, using native grasslands as reference sites, a topic that has not yet been addressed in the region.

High-Andean grasslands play an important role in the carbon cycle, as they store large amounts of SOC [9]. It is also important to note that SOC is the largest terrestrial carbon pool, far exceeding that of the atmosphere [10]. From the perspective of the productive capacity of agro-ecosystems, SOC storage is a key element to consider for their long-term sustainability [11]. However, several studies in different regions of the world show that the SOC content of agricultural lands decreases significantly compared to that of natural ecosystems [12]. Furthermore, the loss of SOC leads to the degradation of the soil structure, infiltration capacity, and primary productivity, which, in turn, leads to soil infertility, changes in the hydrological cycle, and even climatological changes [8,12]. Despite the above-mentioned importance of high-Andean ecosystems, there are no studies that quantify the change in SOC stocks when native grasslands are replaced by croplands, an aspect that may be influenced by the difficulty of access to field studies in the area [9]. Knowing how SOC stocks change in response to land-use change and their environmental controls is important for predicting the effects of these transformations and to support land-use planning and management activities that minimize the impact on this resource.

The amount of organic carbon stored in the soil of a given ecosystem results from the balance between carbon inputs and outputs to the soil reservoir. While net primary productivity is the main pathway of carbon input to the soil, heterotrophic respiration is the main output pathway; however, soil erosion may also be important under certain circumstances [13]. SOC stocks are generally influenced by precipitation, through its effect on primary productivity, and by temperature, through its effect on microbial decomposition rates [14,15]. SOC stocks are also affected by soil texture, through its influence on organic matter stabilization, and by topography, through its influence on water movement and erosion [16]. Changes in land use, such as the replacement of native grassland by annual crops, often alter the balance between the carbon inputs and outputs to the soil pool, which can affect the SOC stocks. Land-use change can affect this balance between inputs and outputs through a number of mechanisms, such as altering microclimatic conditions [17,18], causing changes in the microbial community [19], or altering the quantity and quality of organic detritus [20], among others.

The main goal of this work was to study the variation in SOC storage as a consequence of the replacement of native grasslands by traditional crops in high-Andean systems (>3600 m.a.s.l.) in Peru. Based on previous work, we hypothesized that this land-use change would result in a significant loss of SOC, which may compromise the productivity of the agricultural systems in the long term. For this purpose, soil sampling was carried out at 16 paired sites (croplands and reference grasslands) distributed in the micro-watershed where the rural population of Canrao is located (Huanta Province, Peru). The simultaneous and contiguous availability of these two situations allowed us to apply a space-for-time substitution approach, whereby the native grassland was considered as the original situation before the land-use change [21]. The soil was sampled to a depth of 20 cm for organic carbon analysis and the soil bulk density was also determined at each sampling point. This information was complemented by a satellite analysis based on the NDVI index, which has been widely associated with the aboveground primary productivity of the native vegetation [22,23] and the yield of traditional crops (e.g., maize, soybean, and wheat) [24–26]. Regression analyses between biophysical variables (slope, altitude, and NDVI) and SOC stock were also carried out to analyze the controls of this variable. While the general topic of this paper has been extensively covered in the literature, it should be noted that there is a lack of precedents for this type of study in the region, therefore, this is the first article focusing on the effects of land-use change on SOC content.

2. Materials and Methods

2.1. Study Area

The study area was located in the micro-watershed of the Sullccapallcca stream, near the village of Canrao, Huanta province, Ayacucho department (Peru) (Figure 1). It is representative of the high-Andean ecosystems, and it covers an area of 211 km^2. The average altitude of the micro-watershed is 3929 m.a.s.l., and it varies between 4230 and 3628 m.a.s.l. [27]. The main economic activities are cattle breeding and agriculture. Access to the town is by a road, which is in very poor condition. In the lower parts of the micro-watershed, the natural vegetation is dominated by grasslands, where *Stipa ichu*, *Carex* sp., *Calamagrostis* sp., *Stipa brachyphylla*, *Hipochaeris taraxacoides*, and *Scirpus rigidus* predominate. In the higher parts, areas of bare soil with rocky outcrops predominate, favored by the high slopes that generate rainfall runoff. The grazing system practiced in the study area is continuous, due to the limitations imposed by the relief of the terrain. Likewise, the agriculture is practiced in a conventional manner, due to the steepness of the terrain and the difficulty of access for agricultural machinery. The crops grown are annuals, such as *Solanum tuberosum*, *Oxalis tuberosa*, *Triticum aestivum*, *Hordeum vulgare*, *Zea mays*, and *Lepidium meyenii*, among others. The crops are generally fertilized with organic fertilizers such as cattle manure and, to a lesser extent, bird guano from islands off the Pacific coast.

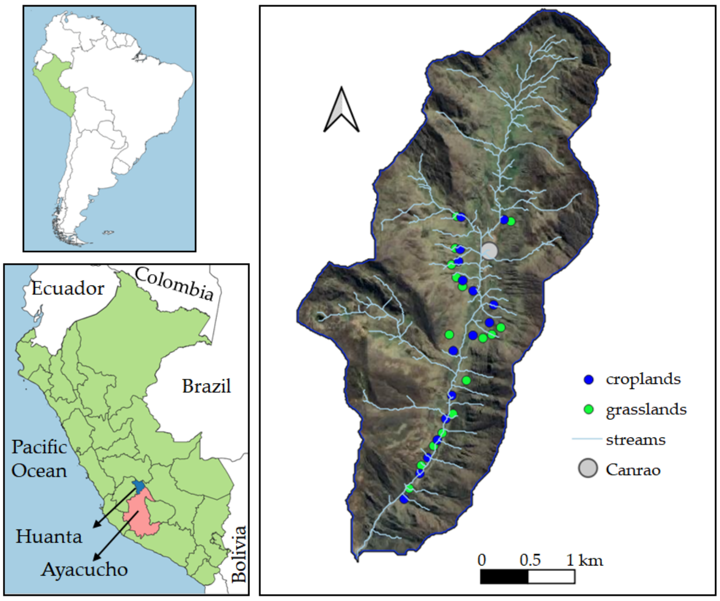

Figure 1. The location of the study area and soil sampling points in croplands and native grasslands. The location of Peru in South America is shown in the upper left panel. The lower left panel shows the location of the province of Huanta, within the department of Ayacucho, where the study was located. The right panel outlines the micro-watershed of the Sullccapallcca stream where the sampling points were located.

The climate of the study area is considered sub-humid, with an average annual rainfall of 850 mm, varying between 500 and 1200 mm in the period of 1981–2010, according to the records of the National Service of Meteorology and Hydrology of Peru (SENAMHI). The average annual temperature is 8 °C, with the coldest month being July (mean monthly temperature of 0 °C) and the warmest month being December (mean monthly temperature of 14 °C). The soils in the upper parts of the study area are Lithosols, which are shallow and established on hard rock stables. These soils are poorly consolidated and are formed by outcrops of sedimentary rocks such as sandstone, limestone, and shale. In contrast, the soils in the lower part are typically Histosols with high vegetation cover [28].

2.2. Soil Sampling and Analysis

In order to investigate changes in SOC storage in the cropland and grassland areas, paired plots were sampled in the studied micro-watershed. To select the sites to be sampled, we first analyzed historical Google Earth images of the Canrao micro-watershed to identify possible sampling points in areas with annual crops and grasslands. Finally, 16 paired sites were established, consisting of cropland and grassland plots used as a reference. The distance between the two plots within each site was always less than 50 m to ensure similar environmental conditions at both sites (e.g., soil, slope, and elevation). The cropland plots have been maintained in this condition for at least the last 35 years. For each sampling point, the geographical position and altitude were recorded with a GPS. Subsequently, 10 soil subsamples were taken from 0- to 20-cm depth in each of the plots, which were then pooled to form a single sample per plot. In order to have unaltered samples for calculating the bulk density of the soil, a steel ring with a diameter of 5.08 cm and a height of 10 cm was used to obtain samples with an exact volume of 202.7 cm^3. All of the samples taken from the field were dried in an oven at 105 °C for 24 h, and the bulk density of the soil was determined using the volume of the ring in relation to the weight of the sample. For this purpose, the homogenized samples were weighed with an analytical balance for calculation using the cylinder method proposed by Blake and Hartge [29]. For the determination of soil organic carbon, air-dried samples were first sieved through a 2-mm mesh and then analyzed via dry combustion. Finally, the soil depth was adjusted to account for changes in bulk density due to land-use change, following Villarino et al. [30]. In some cases, the effect of the land use on SOC stocks per unit area may be slightly underestimated if the soil depth is not adjusted [31], as agricultural soils typically have higher bulk densities than native grassland soils.

The elevation and slope of each sampling plot were determined with a digital terrain model of Alos Palsar with a spatial resolution of 12.5 m per pixel (https://search.asf.alaska.edu/#/?dataset=ALOS, accessed on 3 June 2023). The normalized difference vegetation index (NDVI) was also obtained for each sampled plot as an indicator of the aboveground primary productivity and crop yield [23,24]. For this purpose, images were obtained from the Landsat 8 satellite, which has a spatial resolution of 30 meters and a temporal resolution of 16 days. The images were acquired over a period of nine years (2013–2021). Before calculating the NDVI, the atmospheric correction of the red and near-infrared bands was performed based on the dark-object subtraction (DOS) method proposed by Chavez [32]. The period between October and January was not included in this analysis because of the high cloud cover in the region, which prevents the acquisition of reliable images during this period. NDVI data were extracted from a 2 × 2 pixel area centered on the sampling point. The image processing was carried out using the free software QGIS (Version 3.16; https://www.qgis.org/es/site/, accessed on 3 June 2023). Statistical comparisons were made between the cropland and grassland soils for SOC concentration, SOC stock, bulk density, and environmental variables using paired t-Student tests. Linear regression analyses were also carried out between the SOC stocks in the two ecosystems and the environmental variables. The statistical analyses were performed with R v.3.4.0 (Core Team, R.C, Bethesda, MD, USA, 2017).

3. Results and Discussion

The SOC storage was significantly higher in the grasslands than in the croplands for the sampled horizon of 0–20 cm (Figure 2). On average, the SOC concentration was almost 2% higher in the grasslands than in the croplands (mean SOC concentration of 11.9 vs. 10%, $p < 0.05$). On the other hand, the soil bulk density was slightly higher in the croplands, with a mean value of 1.13 g cm^{-3} compared to 1.06 g cm^{-3} in the grasslands; however, the differences were not statistically significant ($p = 0.15$; Figure 2). Based on these differences, the croplands lost, on average, 27.4 tonnes (Tn) SOC per hectare compared to the grasslands (247.5 vs. 220.1 Tn SOC ha^{-1}, $p < 0.05$). However, when it was corrected for differences in bulk density, this loss increased to 38.7 Tn SOC ha^{-1} ($p < 0.05$; Figure 2).

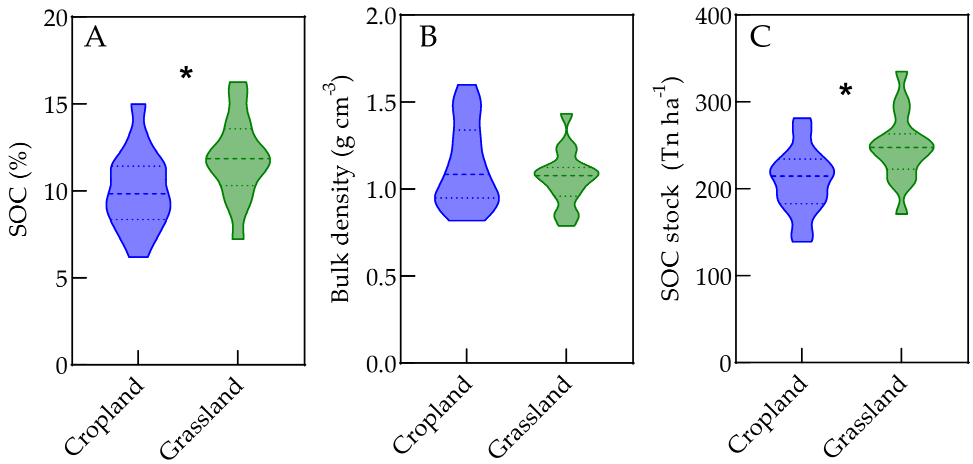

Figure 2. Violin plots for SOC concentration (**A**), bulk density (**B**), and SOC stock (**C**) in grasslands and croplands. The asterisks indicate statistically significant differences ($p < 0.05$).

When analyzing the paired sites individually, it was observed that, at most of the sites, with the exception of four cases, the SOC stock was higher in the grasslands (Figure 3). In this type of vegetation cover, the SOC stock varied between 171 and 335 Tn ha^{-1}, while, in the croplands, it varied between 139 and 281 Tn ha^{-1}. Furthermore, the differences in the SOC stocks ranged from −145 Tn SOC ha^{-1} to +47 Tn SOC ha^{-1} (Figure 3). These differences in SOC stocks between the grasslands and the croplands were strongly associated with the SOC stock of the reference grassland ($r^2 = 0.60$, $p < 0.001$) (Figure 3, inset). That is, the grasslands with higher SOC stocks suffered greater losses when converted to agricultural lands. This pattern is similar to that found in the Argentine Pampas, where the initial SOC stock in pristine soils was found to be the main environmental factor determining carbon losses when the grasslands were converted to croplands [33]. This relationship is important because it would allow us to predict the impact of future land-use change on SOC stocks and identify land-use planning strategies that minimize soil C emissions.

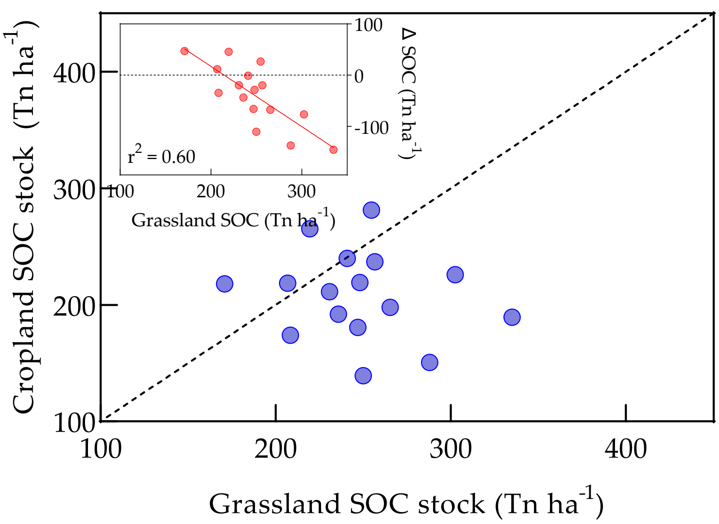

Figure 3. SOC stocks in 16 paired sites (grasslands vs. croplands), with the dashed line indicating the 1:1 line (blue points). The inset graphic shows the relationship between the SOC stock in the grassland and the change in SOC stock after conversion to cropland (red points).

The lower SOC content of the croplands compared to the grasslands is consistent with many studies showing this trend. However, the magnitude of the SOC loss found in this work (−16%) is slightly lower than that reported in other studies. For example, Zhao et al. [34] found that the SOC reserves were up to 79% higher in the grasslands than in the croplands at a depth of 0–60 cm in Inner Mongolia. Similarly, a study conducted in Ethiopia showed that agriculture led to a 69% decrease in SOC reserves compared to that of grasslands at the surface soil layer (0–10 cm) [35]. In the Argentine Pampas, the replacement of native grassland with annual crops reduced the SOC in the first 20 cm of the soil by 25–35% [33]. In general, many studies and meta-analyses show a 30–80% decrease in SOC when grasslands are converted to croplands [36,37]. The lower SOC content of croplands compared to native grasslands is the result of several processes, which may or may not act jointly. These processes include the lower C input from crops due to their lower primary productivity, higher erosion rates, or the increased mineralization favored by higher soil temperatures and aeration [38,39]. In our study, the smaller decline in SOC stocks in the croplands could be due to the contribution of organic fertilizer, which is commonly used in the study region, a practice that would limit carbon loss in agriculture [16]. However, specifically designed field studies would be needed to test this hypothesis. Interestingly, the replacement of high-Andean grasslands in central Ecuador (3500 m.a.s.l.) by fast-growing exotic tree species (*Pinus radiata*)—a widespread transformation in the region [40]—also reduced the SOC content of the surface soils (0–10 cm) by up to one third [41].

The amount of organic carbon stored in the soils of the studied grasslands is relatively high compared to that of other grassland sites. For example, a global review of more than 120 sites showed that temperate grasslands accumulate an average of 117 Tn SOC ha^{-1} [15] in the first meter of the soil profile, therefore, our estimates would be double this (Figure 2). Similarly, in upland grasslands in France, the average SOC stored in the first 20 cm of soil was 90 Tn SOC ha^{-1} [42]. Furthermore, a study carried out in an area close to our study region also showed organic matter concentration values similar to those obtained in this work [43]. Other studies in the high-Andean grasslands of Ecuador [44], Peru [45], Bolivia [46], and Colombia [47] also showed high levels of SOC accumulation in the surface soil. We speculate that the high altitude of the studied sites (>3500 m.a.s.l.), which have a low air temperature, could explain the high SOC stocks observed in the studied grasslands. Although the temperature is low, it would not limit the primary productivity of the grasslands, as shown by the relatively high values of NDVI (Figure 4), therefore, the C input into the soil would remain high. Likewise, the low temperature would limit microbial activity [16] and, therefore, the decomposition rates of organic matter, which would favor the accumulation of the high SOC values observed in this work.

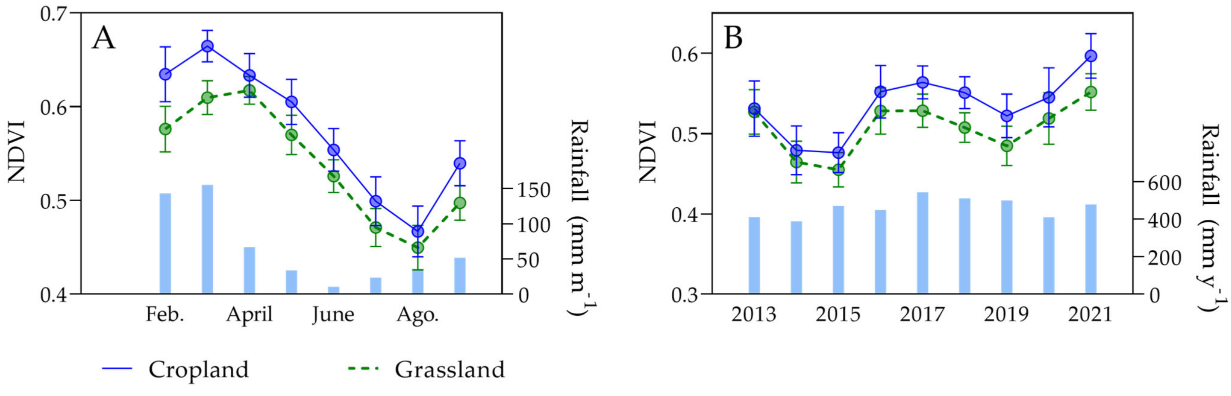

Figure 4. Monthly (**A**) and inter-annual dynamics (**B**) of NDVI in croplands and grasslands. NDVI data were obtained from the Landsat 8 satellite for the period of 2013–2021. Mean values and standard errors are shown. Rainfall data correspond to the Global Precipitation Measurement Mission (GPM) obtained from https://giovanni.gsfc.nasa.gov/giovanni/ (accessed on 1 December 2023).

The SOC stock of the grassland sites was significantly related to the slope of the terrain (Figure 5). In this case, it was observed that the higher the slope, the lower the SOC stock in the grassland, whereas this relationship was not significant in the croplands. This decrease in the SOC stock observed in the grasslands with a slope could be due to its effect on the surface movement and accumulation of water [16]. The sites with higher slopes would favor surface runoff and thus reduce water infiltration into the soil, which could limit grassland productivity and, hence, the SOC inputs. In addition, increased surface water runoff could trigger erosion and redistribution processes that could affect the SOC distribution patterns in the landscape [13,48]. On the other hand, no significant relationship was found between the SOC stocks and the NDVI or elevation (Figure 5). Although elevation has been associated with carbon stocks in some studies [49], it should be noted that the range of elevation variation was very limited in our study. Numerous other environmental factors could explain the spatial variation in SOC content (e.g., rainfall, temperature, soil texture, etc.); however, as our study area was very small, the limited range of variation of these variables prevents us from assessing their influence.

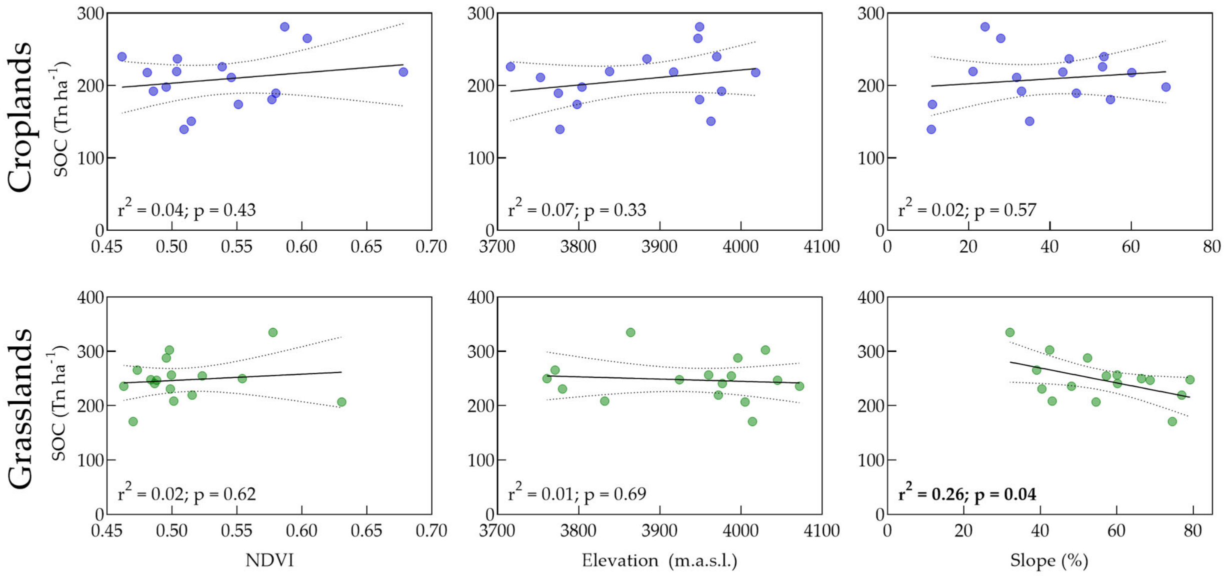

Figure 5. Relationships between environmental variables (NDVI, elevation, and slope) and SOC stocks in croplands (blue points) and grasslands (green points).

The NDVI, a surrogate for aboveground primary productivity [50], was significantly higher in the croplands than in the grasslands. On a monthly basis, the greatest differences between the two vegetation covers were found between the months of February and March, when the NDVI of the croplands exceeded that of the grasslands by up to 10% ($p < 0.05$) (Figure 4A). In turn, the highest NDVI values in both types of vegetation cover were registered between the months of February and April, a period that coincides with the highest rainfall levels in the study region. Both of these ecosystems showed similar inter-annual variability, with the largest differences between the two vegetation types being observed in 2018 and 2021, when the croplands had an NDVI 8% higher than the grasslands (Figure 4B).

The higher NDVI of the croplands, which would imply higher aboveground primary productivity and, therefore, higher C input to the soil, contrasts with the pattern of lower SOC stocks found in this type of land use. Indeed, recent work has shown a strong relationship between the NDVI in native forests and SOC stocks [51]. This apparent discrepancy observed in our study could be partly explained by the different partitioning of primary productivity between the aboveground and belowground components in the two types of vegetation cover studied here. In this sense, a study conducted in the Canadian Great Plains showed that the belowground primary productivity in grasslands accounted for 92% of the total productivity [20]. Similarly, in the Argentinean Pampas, although the aboveground primary productivity of the annual crops was higher than that of the native grasslands, not only was the input of the belowground organic detritus higher in the grassland, but also the aboveground input of C was higher, because a high proportion of the aboveground crop productivity is harvested by humans and exported from the ecosystem [52]. Another aspect that could also explain the lower SOC content in croplands, despite their higher aboveground primary productivity (as suggested by the NDVI), is a higher soil temperature in croplands compared to that of grasslands, as shown in previous studies [53]. The higher soil temperature of croplands would increase the microbial activity and, thus, the organic matter decomposition rates. In any case, field measurements of soil temperature could help us to understand the mechanisms associated with the SOC loss in croplands.

4. Conclusions

From this work, we have concluded that the high-Andean grasslands of Peru are important reservoirs of high levels of SOC (247.5 Tn SOC ha^{-1} for a depth of 0–20 cm). This in turn provides multiple environmental benefits, both local (e.g., soil fertility, water retention capacity, etc.) and global (e.g., climate regulation). However, their conversion to croplands results in a loss of SOC (−16%, $p < 0.05$) that is relatively lower than that observed in other regions for similar land-use conversions. In the long term, however, this loss of SOC could eventually compromise the agricultural productivity and negatively affect other aspects of ecosystem functioning. In this sense, it is essential to propose management strategies to maintain or increase SOC reserves and, thus, the sustainability of the agricultural and livestock production in the region. To this end, it will be necessary to carry out specific work to clarify the mechanisms responsible for the observed patterns and the longer-term trends.

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References

1. Marín, M.A.M.; Pescador, L.R.; Ramos, L.R.; Charry, J.L.A. Impacto de la actividad ganadera sobre el suelo en Colombia. *Ing. Y Región* **2017**, *17*, 1–12. [CrossRef]
2. Brooks, T.M.; Mittermeier, R.A.; da Fonseca, G.A.B.; Gerlach, J.; Hoffmann, M.; Lamoreux, J.F.; Mittermeier, C.G.; Pilgrim, J.D.; Rodrigues, A.S.L. Global Biodiversity Conservation Priorities. *Science* **2006**, *313*, 58–61. [CrossRef] [PubMed]
3. Murillo-Sandoval, P.J.; Clerici, N.; Correa-Ayram, C. Rapid loss in landscape connectivity after the peace agreement in the Andes-Amazon region. *Glob. Ecol. Conserv.* **2022**, *38*, e02205. [CrossRef]
4. Paruelo, J.M.; Guerschman, J.P.; Verón, S.R. Expansión agrícola y cambios en el uso del suelo. *Cienc. Hoy* **2005**, *15*, 14–23.
5. Birkhofer, K.; Diehl, E.; Andersson, J.; Ekroos, J.; Früh-Müller, A.; Machnikowski, F.; Mader, V.L.; Nilsson, L.; Sasaki, K.; Rundlöf, M. Ecosystem services—Current challenges and opportunities for ecological research. *Front. Ecol. Evol.* **2015**, *2*, 87. [CrossRef]
6. Arizapana-Almonacid, M.A.; Pariona-Antonio, V.H.; Castañeda-Tinco, I.; Ascención Mendoza, J.C.; Gutiérrez Gómez, E.; Ramoni-Perazzi, P. Land cover changes and comparison of current landscape metrics in a region of the Central Andes affected by population migration. *Ann. GIS* **2024**, 1–16. [CrossRef]
7. Evrendilek, F.; Celik, I.; Kilic, S. Changes in soil organic carbon and other physical soil properties along adjacent Mediterranean forest, grassland, and cropland ecosystems in Turkey. *J. Arid Environ.* **2004**, *59*, 743–752. [CrossRef]
8. Powlson, D.S.; Gregory, P.J.; Whalley, W.R.; Quinton, J.N.; Hopkins, D.W.; Whitmore, A.P.; Hirsch, P.R.; Goulding, K.W.T. Soil management in relation to sustainable agriculture and ecosystem services. *Food Policy* **2011**, *36*, S72–S87. [CrossRef]

9. Sylvester, S.P.; Heitkamp, F.; Sylvester, M.D.; Jungkunst, H.F.; Sipman, H.J.; Toivonen, J.M.; Gonzales Inca, C.A.; Ospina, J.C.; Kessler, M. Relict high-Andean ecosystems challenge our concepts of naturalness and human impact. *Sci. Rep.* **2017**, *7*, 3334. [CrossRef]
10. Janzen, H.H. Carbon cycling in earth systems—A soil science perspective. *Agric. Ecosyst. Environ.* **2004**, *104*, 399–417. [CrossRef]
11. Teague, R.; Kreuter, U. Managing grazing to restore soil health, ecosystem function, and ecosystem services. *Front. Sustain. Food Syst.* **2020**, *4*, 157. [CrossRef]
12. Lal, R. Soil carbon sequestration to mitigate climate change. *Geoderma* **2004**, *123*, 1–22. [CrossRef]
13. Doetterl, S.; Berhe, A.A.; Nadeu, E.; Wang, Z.; Sommer, M.; Fiener, P. Erosion, deposition and soil carbon: A review of process-level controls, experimental tools and models to address C cycling in dynamic landscapes. *Earth-Sci. Rev.* **2016**, *154*, 102–122. [CrossRef]
14. Homann, P.S.; Kapchinske, J.S.; Boyce, A. Relations of mineral-soil C and N to climate and texture: Regional differences within the conterminous USA. *Biogeochemistry* **2007**, *85*, 303–316. [CrossRef]
15. Jobbágy, E.G.; Jackson, R.B. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecol. Appl.* **2000**, *10*, 397–398. [CrossRef]
16. Wiesmeier, M.; Urbanski, L.; Hobley, E.; Lang, B.; von Lützow, M.; Marin-Spiotta, E.; van Wesemael, B.; Rabot, E.; Ließ, M.; Garcia-Franco, N.; et al. Soil organic carbon storage as a key function of soils—A review of drivers and indicators at various scales. *Geoderma* **2019**, *333*, 149–162. [CrossRef]
17. Houspanossian, J.; Nosetto, M.; Jobbágy, E.G. Radiation budget changes with dry forest clearing in temperate Argentina. *Glob. Change Biol.* **2013**, *19*, 1211–1222. [CrossRef] [PubMed]
18. Magliano, P.N.; Gimenez, R.; Houspanossian, J.; Páez, R.; Nosetto, M.D.; Fernández, R.; Jobbágy, E.G. Litter is more effective than forest canopy reducing soil evaporation in Dry Chaco rangelands. *Ecohydrology* **2017**, *10*, e1879. [CrossRef]
19. Zogg, G.P.; Zak, D.R.; Ringelberg, D.B.; White, D.C.; MacDonald, N.W.; Pregitzer, K.S. Compositional and Functional Shifts in Microbial Communities Due to Soil Warming. *Soil Sci. Soc. Am. J.* **1997**, *61*, 475–481. [CrossRef]
20. Steinaker, D.; Wilson, S. Belowground litter contributions to nitrogen cycling at a northern grassland-forest boundary. *Ecology* **2005**, *86*, 2825–2833. [CrossRef]
21. Nosetto, M.D.; Jobbágy, E.G.; Paruelo, J.M. Carbon sequestration in semiarid rangelands: Comparison of Pinus ponderosa plantations and grazing exclusion in NW Patagonia. *J. Arid Environ.* **2006**, *67*, 142–156. [CrossRef]
22. Jobbágy, E.G.; Sala, O.E.; Paruelo, J.M. Patterns and controls of primary production in the patagonian steppe: A remote sensing approach. *Ecology* **2002**, *83*, 307–319.
23. Paruelo, J.M.; Epstein, H.E.; Lauenroth, W.K.; Burke, I.C. ANPP estimates from NDVI for the central grassland region of the United States. *Ecology* **1997**, *78*, 953–958. [CrossRef]
24. Lopresti, M.F.; Di Bella, C.M.; Degioanni, A.J. Relationship between MODIS-NDVI data and wheat yield: A case study in Northern Buenos Aires province, Argentina. *Inf. Process. Agric.* **2015**, *2*, 73–84. [CrossRef]
25. Nagy, A.; Fehér, J.; Tamás, J. Wheat and maize yield forecasting for the Tisza river catchment using MODIS NDVI time series and reported crop statistics. *Comput. Electron. Agric.* **2018**, *151*, 41–49. [CrossRef]
26. Ren, J.; Chen, Z.; Zhou, Q.; Tang, H. Regional yield estimation for winter wheat with MODIS-NDVI data in Shandong, China. *Int. J. Appl. Earth Obs. Geoinf.* **2008**, *10*, 403–413. [CrossRef]
27. Instituto Nacional de Estadistica e Informatica. Directorio Nacional de Centros Poblados Censos Nacionales 2017: XII de Población, VII de Vivienda y III de Comunidades Indígenas. Tomo 2 Ayacucho, Cajamarca Callao y Cusco. 2018. Available online: https://www.inei.gob.pe/media/MenuRecursivo/publicaciones_digitales/Est/Lib1541/tomo2.pdf (accessed on 1 October 2023).
28. Municipalidad Distrital de Sivia. *Evaluación de Riesgos por Inundaciones Fluvial, en la Localidad de Sivia—Sector río Sivia Mayo, Distrito de Sivia, Provincia de Huanta—Ayacucho*; CENEPRED: Ayacucho, Peru, 2019.
29. Blake, G.; Hartge, K. Bulk density. In *Methods of Soil Analysis: Part 1. Physical and Mineralogical Methods*; Klute, A., Ed.; Wiley: Madison, WI, USA, 1986; pp. 363–375.
30. Villarino, S.H.; Studdert, G.A.; Baldassini, P.; Cendoya, M.G.; Ciuffoli, L.; Mastrángelo, M.; Piñeiro, G. Deforestation impacts on soil organic carbon stocks in the Semiarid Chaco Region, Argentina. *Sci. Total Environ.* **2017**, *575*, 1056–1065. [CrossRef]
31. Post, W.M.; Kwon, K.C. Soil carbon sequestration and land-use change: Processes and potential. *Glob. Change Biol.* **2000**, *6*, 317–327. [CrossRef]
32. Chavez, P.S., Jr. Radiometric calibration of Landsat Thematic Mapper multispectral images. *Photogramm. Eng. Remote Sens.* **1989**, *55*, 1285–1294.
33. Wyngaard, N.; Crespo, C.; Angelini, H.; Eyherabide, M.; Larrea, G.; Reussi Calvo, N.; Carciochi, W.; Sainz Rozas, H. The effect of agriculture on topsoil carbon stocks is controlled by land use, climate, and soil properties in the Argentinean Pampas. *CATENA* **2022**, *212*, 106126. [CrossRef]
34. Zhao, W.; Hu, Z.; Li, S.; Guo, Q.; Yang, H.; Zhang, T. Impact of land use conversion on soil organic carbon stocks in an agro-pastoral ecotone of Inner Mongolia. *J. Geogr. Sci.* **2017**, *27*, 999–1010. [CrossRef]
35. Shiferaw, A.; Yimer, F.; Tuffa, S. Changes in soil organic carbon stock under different land use types in semiarid Borana rangelands: Implications for CO_2 emission mitigation in the rangelands. *J. Agric. Sci. Food Res.* **2019**, *10*, 254. [CrossRef]
36. Guo, L.B.; Gifford, R.M. Soil carbon stocks and land use change: A meta analysis. *Glob. Change Biol.* **2002**, *8*, 345–360. [CrossRef]

37. Poeplau, C.; Don, A.; Vesterdal, L.; Leifeld, J.; Van Wesemael, B.; Schumacher, J.; Gensior, A. Temporal dynamics of soil organic carbon after land-use change in the temperate zone—Carbon response functions as a model approach. *Glob. Change Biol.* **2011**, *17*, 2415–2427. [CrossRef]
38. Hassink, J.; Whitmore, A.P.; Kubát, J. Size and density fractionation of soil organic matter and the physical capacity of soils to protect organic matter. *Eur. J. Agron.* **1997**, *7*, 189–199. [CrossRef]
39. Balesdent, J.; Chenu, C.; Balabane, M. Relationship of soil organic matter dynamics to physical protection and tillage. *Soil Tillage Res.* **2000**, *53*, 215–230. [CrossRef]
40. Farley, K.A.; Bremer, L.L.; Harden, C.P.; Hartsig, J. Changes in carbon storage under alternative land uses in biodiverse Andean grasslands: Implications for payment for ecosystem services. *Conserv. Lett.* **2013**, *6*, 21–27. [CrossRef]
41. Farley, K.A.; Kelly, E.F.; Hofstede, R.G. Soil organic carbon and water retention after conversion of grasslands to pine plantations in the Ecuadorian Andes. *Ecosystems* **2004**, *7*, 729–739. [CrossRef]
42. Soussana, J.F.; Loiseau, P.; Vuichard, N.; Ceschia, E.; Balesdent, J.; Chevallier, T.; Arrouays, D. Carbon cycling and sequestration opportunities in temperate grasslands. *Soil Use Manag.* **2004**, *20*, 219–230. [CrossRef]
43. Aguilar, S.Y. *Validación del Método de Calcinación en la Determinación del Contenido de la Materia Orgánica del Suelo*; Universidad Nacional Agraria La Molina: Lima, Peru, 2019.
44. Ayala, L.; Villa, M.; Mendoza, Z.A.; Mendoza, N.A. Cuantificación del carbono en los páramos del parque nacional Yacuri, provincias de Loja y Zamora Chinchipe, Ecuador. *Cedamaz* **2014**, *4*, 45–52.
45. Yang, S.; Jansen, B.; Kalbitz, K.; Chunga Castro, F.O.; van Hall, R.L.; Cammeraat, E.L. Lithology controlled soil organic carbon stabilization in an alpine grassland of the Peruvian Andes. *Environ. Earth Sci.* **2020**, *79*, 66. [CrossRef]
46. Mamani, R.P. *Evaluación del Contenido de Carbono Orgánico del Suelo en la Región Andina de Bolivia*; Universidad Mayor de San Andrés: La Paz, Bolivia, 2021.
47. Montes Pulido, C.R. *Cuantificación del Carbono Orgánico en el Suelo Bajo dos Tipos de uso, en el Ecosistema de Páramo de Sumapaz, Cundinamarca, Colombia*; Universidad Católica "Santa Teresa de Jesús" de Ávila: Ávila, Spain, 2015.
48. Tan, Z.X.; Lal, R.; Smeck, N.E.; Calhoun, F.G. Relationships between surface soil organic carbon pool and site variables. *Geoderma* **2004**, *121*, 187–195. [CrossRef]
49. Leifeld, J.; Bassin, S.; Fuhrer, J. Carbon stocks in Swiss agricultural soils predicted by land-use, soil characteristics, and altitude. *Agric. Ecosyst. Environ.* **2005**, *105*, 255–266. [CrossRef]
50. Goward, S.N.; Dye, D.G. Evaluating North American net primary productivity with satellite observations. *Adv. Space Res.* **1987**, *7*, 165–174. [CrossRef]
51. Peri, P.; Gaitán, J.; Mastrangelo, M.; Nosetto, M.D.; Villagra, P.E.; Balducci, E.; Pinazo, M.; Eclesia, R.P.; Von Wallis, A.; Villarino, S.; et al. Soil organic carbon stocks in native forest of Argentina: A useful surrogate for mitigation and conservation planning under climate variability. *Ecol. Process.* **2024**, *13*, 1. [CrossRef]
52. Frasier, I.; Barbero, F.M.; Pérez-Brandan, C.; Gómez, M.F.; Fernández, R.; Quiroga, A.R.; Posse-Beaulieu, G.; Restovich, S.; Meriles, J.; Serri, D.L. Roots are the key for soil C restoration: A comparison of land management in the semiarid Argentinean Pampa. *Soil Tillage Res.* **2024**, *235*, 105918. [CrossRef]
53. Nosetto, M.D.; Jobbágy, E.G.; Brizuela, A.B.; Jackson, R.B. The hydrologic consequences of land cover change in central Argentina. *Agric. Ecosyst. Environ.* **2012**, *154*, 2–11. [CrossRef]

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