

Article

Seasonal Effects of Wildfires on the Physical and Chemical Properties of Soil in Andean Grassland Ecosystems in Cusco, Peru: Pending Challenges

Melida Roman ^{1,2}, Ricardo Zubieta ^{1,*} , Yerson Ccanchi ^{1,3} , Alejandra Martínez ⁴, Ysai Paucar ² ,
Sigrid Alvarez ^{2,4}, Julio Loayza ² and Filomeno Ayala ²

¹ Subdirección de Ciencias de la Atmósfera e Hidrosfera, Instituto Geofísico del Perú (IGP), Lima 15494, Peru; 132058@unsaac.edu.pe (M.R.); yccanchi@igp.gob.pe (Y.C.)

² Escuela Profesional de Ingeniería Agropecuaria, Facultad de Agronomía y Zootecnia, Universidad Nacional San Antonio Abad del Cusco (UNSAAC), Andahuaylas 03700, Peru; ysai.paucar@unsaac.edu.pe (Y.P.); 151648@unsaac.edu.pe (S.A.); julio.loayza@unsaac.edu.pe (J.L.); filomeno.ayala@unsaac.edu.pe (F.A.)

³ Programa de Maestría en Recursos Hídricos, Escuela de Postgrado, Universidad Nacional Agraria La Molina (UNALM), Lima 15012, Peru

⁴ Subdirección de Geofísica y Sociedad, Instituto Geofísico del Perú (IGP), Lima 15494, Peru; amartinez@igp.gob.pe

* Correspondence: rzubieta@igp.gob.pe

Abstract: Soils are a valuable renewable resource on human timescales, and they interact with distinctive grassland ecosystems characterized by unique biodiversity and essential provision of ecosystem services, such as water supply and carbon sequestration. However, knowledge of the effects of wildfires on soil properties and nutrient availability in the Andes remains limited. Andean grasslands are currently one of the ecosystems of the Peruvian Andes most affected by wildfires. Our objective is to analyze the effect of fire activity on the physicochemical properties of soil and analyze its social context in Cusco, in the southern Andes of Peru. Soil samples were collected during five periods, spanning both the dry and rainy seasons, to characterize changes in soil properties and monitor vegetation recovery post-fire in two local communities dedicated to livestock activities. The vegetation restored after the wildfire was measured by the “step transect” method. Post-fire changes in soil properties indicate slight increases in pH, electrical conductivity, organic matter, nitrogen, phosphorus, and potassium during the onset of the rainy season; thereafter, a gradual reduction in these values was observed. This reduction can be attributed to leaching associated with the seasonal rainfall and runoff regime. Our findings indicate that one-year post-fire, the biomass in burned areas is reduced to 30–46% of the biomass in unburned areas. A complete regeneration is likely to occur in up to 4 years; this assertion is supported by the perceptions of the affected population, as expressed in interviews conducted in the two farming communities. These results are significant for decision-makers formulation of policies and regulations regarding grasslands and their seasonal restoration.

Keywords: wildfire; soil property; fire prevention; grassland; Andes



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1. Introduction

The Andean region of South America harbors one of the world’s most biodiverse montane ecosystems [1,2]. Tropical Andean plant diversity is remarkably vast, and habitat types are interconnected [3,4]. Pastoralism is the main land use in the humid tropical Andes [5]. Wide areas of mountain grasslands in the Andes are currently used for pasturing livestock [6]. The high Andean grasslands are distinctive ecosystems characterized by high biodiversity and essential provision of ecosystem services [7], such as soil conservation, supporting food production, mitigating drought and floods, maintaining biodiversity, and offering research opportunities, among others [8]. Natural grasslands are regenerated

by processes related to climate, fire, and grazing [9]. These ecosystems are fragile and face significant threats characterized by marked climatic conditions [10]. Wildfires can also significantly impact the chemical, physical, and biological properties of soil because of the frequency, duration, and intensity of burning [11]. Indeed, soil plays a crucial role in supporting plant growth through nutrient cycling, mineral storage, and carbon sequestration [12,13]. Degradation of the biological, chemical, and physical properties of soils can temporarily or permanently limit the capacity for plant growth, suggesting that immediate fire impacts are concentrated in the surface soil horizon [14]. The soils in these ecosystems sustain native grasslands (*Poaceae*, *Asteraceae*, among others) that serve as the primary food source for livestock. In Peru, Andean grasslands are usually the ecosystems most affected by the wildfires that occur every year between August and November [15]. Eighty percent of fires in Peru occur in the Andes, where the role of the population is undeniable, as grassland fires are often caused by human activity [16,17]. Approximately 5.7 million people self-identify as Indigenous or native to the Andes in Peru; they are mainly dedicated to economic activities such as agriculture, livestock, and commerce, among others [18]. Grasslands play a vital role in livestock production as an economic activity in Peru, which has about 85% of the world's total population of alpacas (*Vicugna Pacos*), with around 4.5 million [19]. However, fire activity in the context of climate change could limit vegetation succession by influencing the composition of plant communities and soil properties [6,20].

Prescribed burning can be defined as the deliberate use of low-intensity or controlled fire, a technique used in various countries to reduce the impacts of fire, contingent upon factors such as climate conditions, forest fuel, and topography [21–24]. However, fire activity clearly alters the environment, including effects on soil properties, which can be positive, neutral, or negative. Most studies suggest that soil tends to recover when soil heating is limited, and fire severity is low [25]. For instance, studies in Spain nine years after prescribed fires reveal that certain chemical and physical properties of forest soil tend to decrease (with some exceptions, such as soil texture and invertebrate biomass) [13,26]. In contrast, a study in Brazil conducted by Santana et al. [27] found that fire increased some chemical properties while decreasing potential acidity and phosphorus content in the soil, with no observed alteration in physical soil properties due to the wildfire.

The impact of fire on soil properties, therefore, can be relative, yielding significantly different outcomes depending on biological, chemical, and physical factors. The extent of soil disturbance by wildfire depends on various factors, including fire intensity, duration, recurrence, fuel load, and soil characteristics. This soil disturbance is evidenced in studies conducted across different regions, such as the USA [23,28], Europe [19,22,29–32], and Asia [33,34]. In the long term, however, clear changes can be observed in the relative abundance of plant growth forms following a fire [35]. The impact of burning and grazing on soils may primarily affect physical characteristics, but changes in chemical properties may not necessarily translate into differences in vegetation structure between grazed, burned, and undisturbed sites [14]. Indeed, the implementation of strategic restoration activities would not evidence improvement in soil conditions in the short term (three years); rather, some properties tend to deteriorate even more in grasslands [36]. In this paper, the term “wildfire” is used to describe any unplanned and uncontrolled fire that occurs in grasslands as a result of burning practices. Low-severity fire activities, such as controlled burns, could have positive effects by accumulating organic matter in the soil as a result of the incomplete combustion of biomass [37]. However, ashes produced during wildfires resulting from burns could also affect soil properties [38,39].

To predict fires and limit their impacts, new knowledge is needed about fire activity and the spatial and temporal distribution of factors linked to its occurrence. This is of utmost importance for agroforestry management and to reduce environmental degradation [40]. Nevertheless, the impacts of wildfires resulting from burning practices have not been fully studied in Peruvian ecosystems. The objective of this study was to analyze the effect of fire activity on soil physicochemical properties and analyze its social context in Cusco, Peru,

through two wildfire emergencies reported by the government. It is important to note that in Peru, prescribed burning is not regulated; thus, all fire activity can be considered burning practices or wildfires.

2. Materials and Methods

2.1. Study Area

Cusco is the historical capital of Peru, situated in southern Peru ($13^{\circ}31'20''$ S $71^{\circ}59'00''$ W). The city's archaeological sites, cultural and ethnic diversity, landscapes, and natural areas have established Cusco as Peru's premier tourist destination [41]. The Cusco region boasts altitudes reaching up to 6300 m above sea level (masl.), with a mean altitude of 3400 masl. (Figure 1a). This area of Peru displays a significant variation in annual precipitation, with the northwestern part, in the Amazon region, experiencing the highest accumulation (5000–8000 mm/year), while the southern zone, in the Andean region, receives the lowest annual rainfall (200–1000 mm/year) [42]. Herbaceous grassland is predominant in the Andean mountains of Cusco between 3000 and 4400 masl. [43]. Cusco is one of the regions most severely affected by wildfires in Peru [44] and has witnessed a significant increase (250%) in wildfire occurrence during extreme drought periods, such as those in 2005 and 2010 [45,46]. Moreover, the COVID-19 pandemic played a role in the increased occurrence of wildfires during 2020 because of migration from urban areas to rural agricultural activities [17].

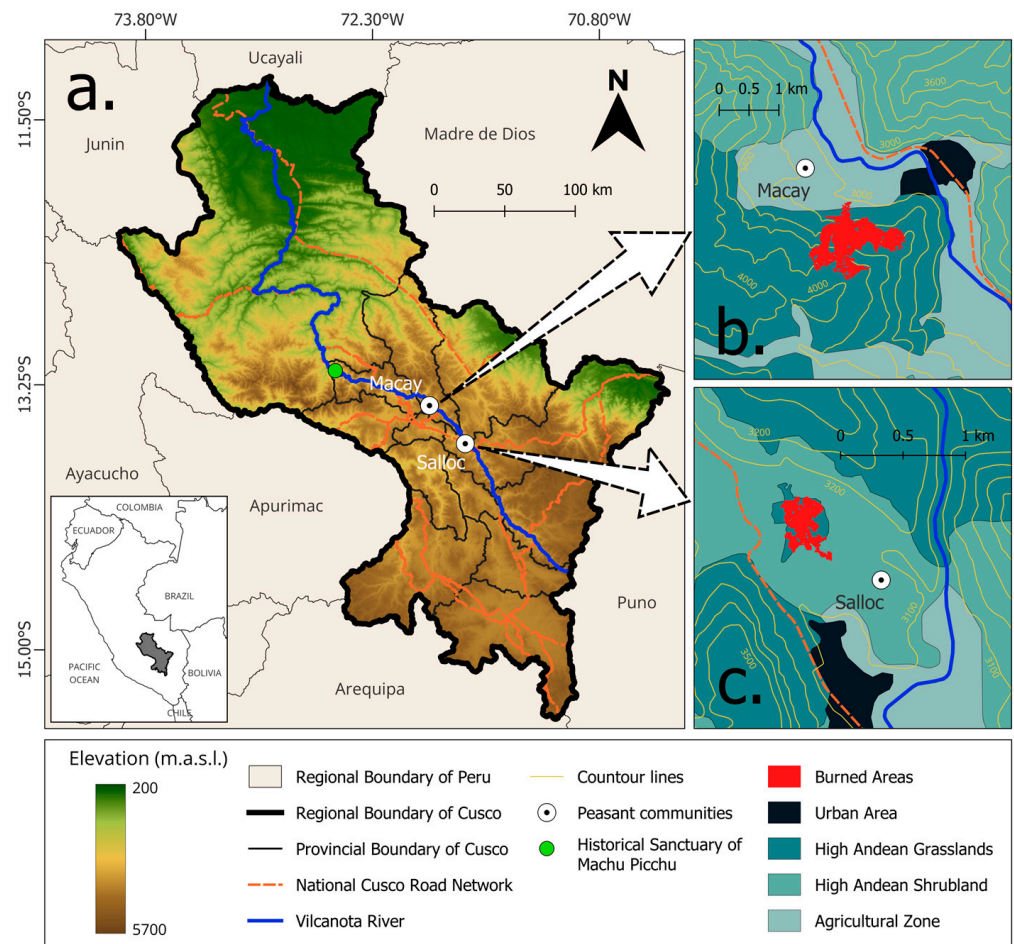


Figure 1. (a) Study area designated for monitoring soil properties and conducting interviews for the (b) Macay and (c) Salloc communities of Cusco. A modified vegetation cover map is shown in (b,c) [43].

A recent study of fire activity in the mountainous region of Cusco shows that only 4% of documented fire incidents are classified as wildfire emergencies, while unauthorized burning practices account for the remaining 96% [47]. The dynamic of fire activity in Cusco is significantly influenced by burning practices associated with agriculture and livestock [17]. It is important to mention that burning practices used by Peru’s Andean population are prohibited by regulations [48,49]. Indeed, controlled burning is not currently regulated. The present study was conducted in the Calca and Quispicanchis provinces, specifically in the Macay and Salloc Indigenous communities of Cusco, respectively (see Figure 1b,c). The area’s lithology is characterized by limestones and volcanic-sedimentary successions [50]. A brief characterization of the study area is presented in Table 1. The study areas were selected based on wildfire emergency reports provided by the National Civil Defense Institute (INDECI-Peru). Wildfires occurred in grasslands, which are the most representative ecosystems in the study area (Figure 1b,c).

Table 1. Characteristics of the study area and wildfire incidence.

Peasant Community	Macay	Salloc
Province	Calca	Quispicanchi
District	Calca	Andahuaylillas
Altitude	2944 masl.	3524 masl.
Average slope	33.0°	3.4°
Latitude	13.387 S	13.639 S
Longitude	71.923 W	71.686 W
Celsius temperature	10°–25°	5°–9°
Main economic activity	Agriculture (potatoes, corn, etc.), Livestock (cattle and sheep)	Agriculture (corn, etc.), Livestock (cattle and sheep)
Main species	<i>Stipa ichu</i> , <i>Poa annua</i> , <i>Calamagrostis intermedia</i>	<i>Pennisetum clandestinum</i> , <i>Paspalum vaginatum</i> , <i>Melinis minutiflora</i>
Characteristics	Wildfire	Wildfire
Approximate duration	15:00–19: 00 h	14:30–18:00 h
Date	23 August 2022	30 August 2022
Affected area	94 ha.	13 ha.
Affected Vegetation	Grassland	Grassland

To establish a connection between this study’s findings and the local population’s perceptions, interviews were conducted with residents of the communities of Macay and Salloc during the fire season (August to December) in 2023. To limit data saturation, a reduced number of interviews (10) were conducted in each peasant community during the final period of the study (Figure 2). Data saturation refers to repetitive and consistent information. Limiting data saturation could be an important criterion for determining the number of interviewees necessary [51]. Indeed, a focus on particular details frustrates the emergence of common patterns, shared meanings, and normative recommendations [52]. Open-ended questions were asked in structured interviews [17]. These were conducted with individuals ranging from ages 22 to 70, all of whom were engaged in agriculture; 90% were women and 10% men. The fact that a high percentage of people interviewed in homes were women could be linked to the time of the interviews (8:00–12:00 h), which coincided with household tasks. Throughout the interviews, information related to burning and wildfires was collected, as all interviewees either had personal experience with conducting burns or had been affected by a wildfire.

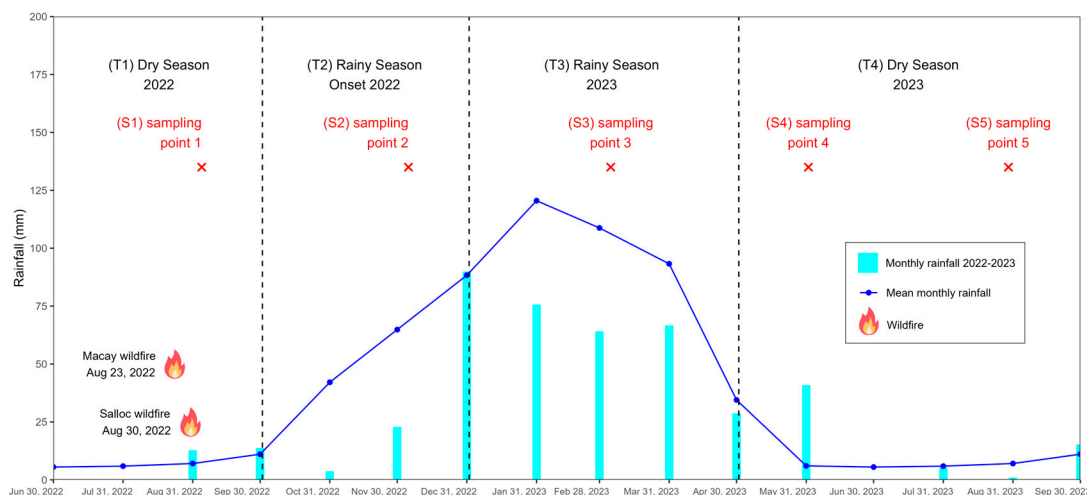


Figure 2. Rainfall pattern 2022–2023 and sampling (S1, S2, S3, S4, S5) of soil properties in Cusco performed during the dry season (T1), rainy season onset (T2), rainy season (T3) and dry season (T4).

2.2. Analyses of Physicochemical Properties of Soil

To assess the impact of fire on the physicochemical properties of soil, sampling points were prioritized in the communities of Macay and Salloc. Pits were opened (30 × 30 cm excavations) to a maximum depth of 10 cm. Samples were taken from the burned (3) and unburned (1) areas; i.e., four points were established in each study area. Samples from two depths (0 to 3 cm and 3 to 10 cm) were obtained; eight soil samples were collected at each study area (Macay and Salloc). Soil sampling (S1, S2, S3, S4, and S5) was conducted at different times, corresponding to the dry season (T1), the onset of the rainy season (T2), rainy season (T3), and subsequent dry season (T4) on September 04–07, December 04–05, March 04–05, June 01–02, and August 29–30, (01, 15, 27, 39 and 51 weeks post-fire, respectively) (Figure 2). Approximately ½ kg of the substrate was extracted using a metal shovel. The material was collected and placed inside previously coded bags to be taken to the laboratory for analysis. The samples were dried, some organic waste was subsequently removed, and the samples were then sieved and stored for subsequent analysis. A detailed description of the process is provided by Van Reeuwijk [53].

The sampling period was selected because of the potential influence of rainfall variability on soil properties in the short and medium term, particularly given the morphology and climatic characteristics of grassland ecosystems, which experience marked seasonal rainfall patterns [54] leading to soil erosion processes in this ecosystem type [55]. The burned areas studied have an average slope between 3% and 33%.

To maintain sample consistency and minimize potential variations that could affect the results, two depths, at 3 and 10 cm, were considered when extracting subsamples from both Macay and Salloc. This approach aligns with the method proposed by Hofstede [14]. During this process, the soil surface in contact with the ash layer was carefully scraped with a razor to remove any carbonized residue. Soil samples were then collected in plastic bags and transported to the soil laboratory at San Antonio Abad National University in Cusco.

Soil texture was determined using the hydrometer method [56], while soil pH was measured with a pH meter following standard procedures [57]. Soil nitrogen concentration (N) (%) was assessed using the Micro-Kjeldahl method [58], and soil organic matter (OM) (%) was determined using the Walkley and Black method [59]. Potassium (K) (ppm) was estimated using the NH₄ method [60], while available soil phosphorus (P) (ppm) was determined using the modified Olsen method [61]. Electrical conductivity (mmhos/cm) (EC) was evaluated using a conductivity meter.

2.3. Biomass Estimation

The modified K.W. Parker method [62], known as the “step transect,” involves collecting samples along transects [63]. Triple steps were taken along these transects, and the types of plants and vegetation cover were recorded. These observations were made in both the burned and unburned areas of Macay and Salloc. In the center of each transect, a 1 m² quadrant was randomly established, and vegetation was cut and placed in paper bags. Biomass was determined using the destructive harvesting method [64], which involves cutting selected vegetation at ground level using a sickle [65]. Samples from each quadrant were cut and placed in previously coded paper bags.

To estimate the richness of the vegetation based on the number of species and their relative proportion in burned and unburned areas, the Shannon diversity index was used [66,67]. The Shannon index normally varies from 1 to 5; values less than 1.6 are referred to as low diversity, values between 1.6 to 3.5 are referred to as medium diversity, and values greater than 3.5 as high diversity [11]. Subsequently, dry matter was obtained by drying the samples in an oven at a temperature of 60 °C for 48 h, following the gravimetric method, 60 °C × 48 h [68]. The weight was then determined using a precision scale. Overall, this method was employed to document “floristic diversity” and estimate biomass in areas affected and unaffected by fire. Floristic diversity is a pivotal component within Andean ecosystems; the term refers to the array of plant species within a specific locale [69]. Characteristics of the transects considered for biomass estimation in communities are described in Table 2.

Table 2. Characteristics of the transects established for biomass estimation in the communities of Macay and Salloc.

Characteristics	Macay		Salloc	
	Unburned Area	Burned Area	Unburned Area	Burned Area
Number of transects	2	2	2	2
Longitudinal dimension of the transects	300 m.	300 m.	100 m.	100 m.
Elevation masl.	3177	3187	3105	3106
Slope	33°	31°	3°	5°
Number of quadrants	2	2	2	2
Quadrant dimension	1 m ²	1 m ²	1 m ²	1 m ²

2.4. Statistical Analysis

An exploratory data analysis was conducted previously to assess the data distribution and identify outliers. Although no outliers were detected, the data nonetheless did not exhibit a normal distribution. Non-parametric statistics were therefore employed. To assess the effects of fire on soil physicochemical properties (pH, electrical conductivity, nitrogen, organic matter, phosphorus, potassium) and biomass accumulation, the Mann-Whitney U test was used [70]. This non-parametric test was used to compare the medians of two independent samples and ascertain whether they were equal. A significance level of 0.05 was employed for all analyses using the R software 4.3.2 v.

2.5. Estimation of Severity of the Burned Areas

Finally, Sentinel-2 scenes more approximate to daytime wildfires that occurred in Macay and Salloc were collected to estimate wildfire severity. Satellite scenes for 17 August 2022 (prior to burning) and 27 August 2022 (after burning) were collected for Macay, while satellite scenes for 27 August 2022 (prior to burning) and 1 September 2022 (after burning) were collected for Salloc. For the preliminary delineation of the affected burned area (pixels identified as burned), the Normalized Burned Ratio (NBR) [71] for each Sentinel-2 scene acquired was computed. The NBR employs reflectivity data from the near-infrared and

short-wave infrared bands. It is used to map burned regions. Its calculation is outlined as follows:

$$NBR = \frac{\rho NIR - \rho SWIR}{\rho NIR + \rho SWIR} \tag{1}$$

where ρNIR and $\rho SWIR$ correspond to 8 A and 12 bands, respectively, of the Sentinel-2 images. Its calculation allows the estimation of the severity of the fire from the difference between the NBR prior to burning and the NBR after burning (dNBR). dNBR values ranging from 0.1 to 1.3 indicate burned areas at varying degrees of severity. A value of 0.1 corresponds to low-severity burned areas, while a value of 1.3 represents high-severity burned areas [71]. In this paper, dNBR values lower than 0.1 are considered unburned, dNBR values between 0.1 and 0.27 are considered low severity, dNBR values between 0.27 and 0.44 are considered moderate-low severity, dNBR values between 0.44 and 0.66 are considered moderate-high severity, and dNBR values higher than 0.66 are considered high severity. A similar scale of dNBR values is proposed in studies of wildfires using satellite images [47,72–76].

3. Results

3.1. Perception of the Population

Local people mention two primary reasons for using fire: (a) to clear land to expand agricultural areas (eliminating weeds and stubble) and (b) to rejuvenate grasslands during the latter part of the year. Burnings are typically organized by smaller community groups, which assume the primary coordinating role. There is also a consensus among the interviewees that burning enhances the fertility of uncultivated soils. Nevertheless, it is also noted that the time required for complete recovery of grasslands after burning or wildfire can vary between one and four years. A brief overview of interviews is presented in Table 3.

Table 3. Synthesis of social perspectives and perceptions gathered from interviews conducted around Macay and Salloc during the 2023 fire season.

Question	Social Opinion
Who is involved in fire use?	Residents dedicated to activities such as agriculture or livestock are the ones who use fire. This occurs mainly in the morning to avoid intense winds (a potential factor in fire expansion), which occur mainly in the afternoon.
What is the objective of burning?	Eliminating weeds and stubble to expand cropland. Renewing grasslands. Limiting the uncontrolled growth of vegetation.
What is the season in which the burnings take place?	June, July, August, and September (for preparing the ground for the next agricultural campaign). April, May, October, and November (for grassland renewal).
Who usually participates during the burning?	Families take responsibility for managing the fire to prevent its spread, along with people who have expertise in burning practices.
Does the burning of grasslands improve soil fertility?	Yes, grassland burning enhances soil fertility by providing ash that can act as a fertilizer.
After a fire, what is the process of grassland recovery, in terms of both quantity and quality and what is the typical timeframe for this recovery?	The post-fire recovery of grassland can vary in both quantity and quality. Sometimes, the grassland remains unchanged, while in other cases, there is a decrease in quantity (likely due to root damage). Full recovery may take several years, typically ranging from one to four years after the fire.

3.2. Wildfire Severity

dNBR values ranging from 0.1 to 1.3 indicate burned areas at varying degrees or levels of severity (Figure 3a,b). Our results indicate that the wildfire in Macay reached levels between low and moderate-high severity (Figure 3a), while the wildfire in Salloc mainly reached levels between low and moderate-low severity (Figure 3b). The slightly higher levels of fire severity in Macay compared to Salloc can be associated with terrain morphology. A greater slope is clearly identified in the area of the Macay fire (10–50°) compared to Salloc (2–5°) (Figure 3c,d). Slope can be considered an important variable in wildfire studies because wildfire severity on vegetation cover tends to be higher in areas

with steeper slopes [77,78]. This is consistent with areas (density of pixels identified in the satellite image as burned area) with slopes of around 30° (Figure 3c). However, this is not observed in an analysis of the burned area in Salloc, which is relatively flat (Figure 3d).

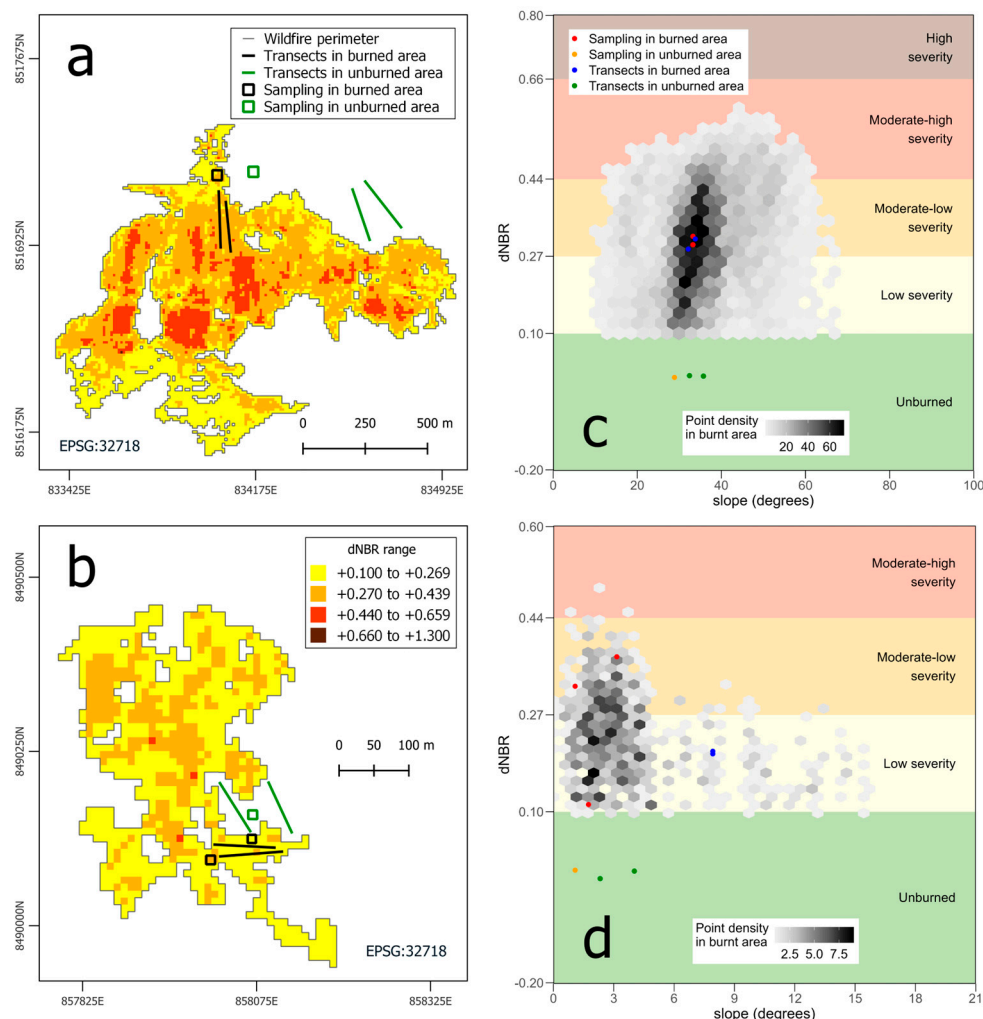


Figure 3. Delimitation by Differenced Normalized Burned Area Index (dNBR) [71] for wildfires in the communities of (a) Macay and (b) Salloc. Locations of transects for biomass estimation are graphed for Macay (a) and Salloc (b). The density of pixels identified in the satellite image according to the dNBR level and slope for the wildfires that occurred in (c) Macay and (d) Salloc.

3.3. Changes in Soil Properties

Figures 4 and 5 summarize the effects of wildfire severity on the physicochemical properties of soil at depths of 0–3 and 3–10 cm, as sampled (S1, S2, S3, S4, S5) in Macay and Salloc during the 2022–2023 period (T1, T2, T3, T4, see Figure 2).

An average of subsamples was considered for each stage to illustrate changes in soil properties (Figures 4 and 5). For example, the results for Macay indicate that surface alkalinity levels (0–3 cm), estimated from pH, exhibit a slight increase in the burned surface compared to the unburned surface between the end of the 2022 dry season and the onset of the rainy season in 2022–2023 (Figure 4a). In contrast, alkalinity levels on the burned surface show a decrease between the 2023 dry season and the onset of the rainy season in 2023–2024 relative to the unburned surface (Figure 4a). It is important to note that a clear difference between burned and unburned surfaces at a depth of 3–10 cm is not observed (Figure 4a).

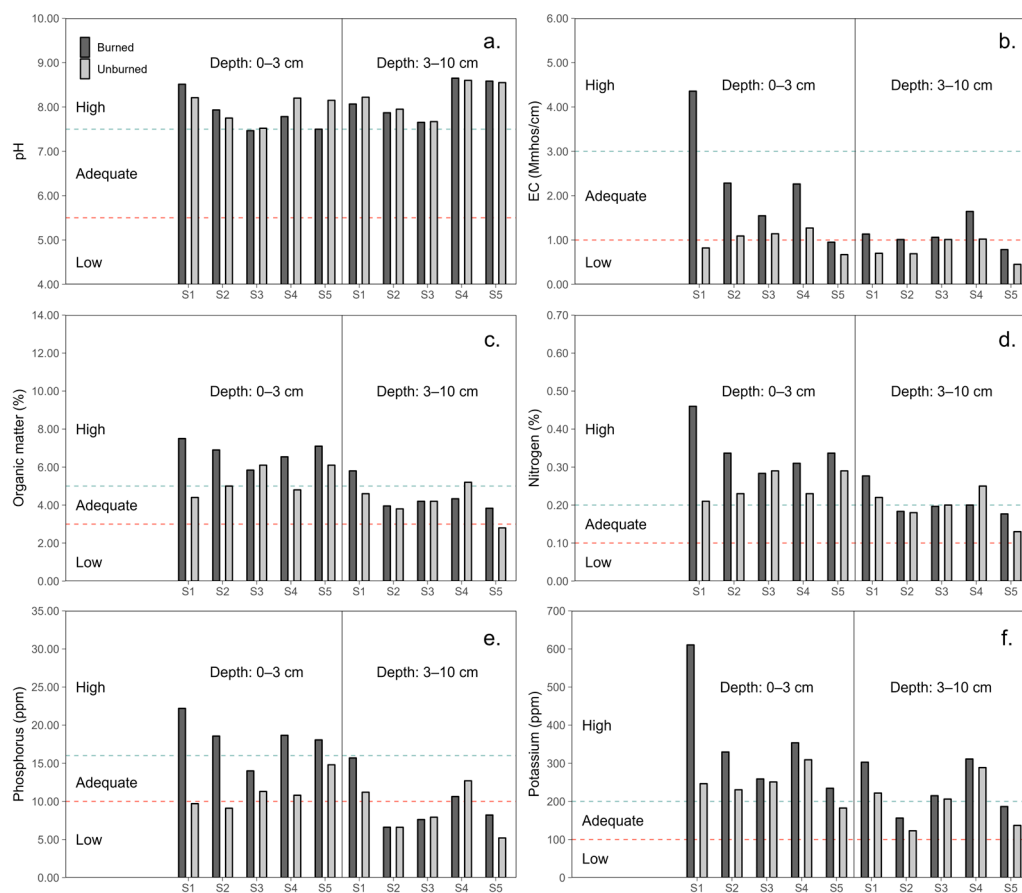


Figure 4. Variations in (a) pH, (b) electrical conductivity, (c) organic matter, (d) nitrogen, (e) phosphorus, and (f) potassium properties at depths of 0–3 cm and 3–10 cm in Macay. The climatic seasonal periods associated with the samples (S1, S2, S3, S4, and S5) are detailed in Figure 2. Thresholds (high, adequate, low) linked to soil fertility in the Andean region [79] are also graphed.

After the wildfire, EC levels (0–3 cm) on burned surfaces exhibit a slight increase persisting up to a year later compared to unburned surfaces, which can be characterized as slightly saline or salt-free. Conversely, EC levels for depths between 3 and 10 cm do not show changes (Figure 4b). Similar to EC values, organic matter (OM) at the surface level (0–3 cm) of burned surfaces demonstrates a predominant increase when compared with unburned surfaces over the course of the year; however, these changes are not observed when OM at a depth of 3–10 cm is analyzed (Figure 4c). A pattern comparable to that of OM is also observed when nitrogen (N) and phosphorus (P) are analyzed at the surface level (0–3 cm) and subsurface (3–10 cm) (Figure 4d,e). A different trend is noted when potassium (K) is evaluated; indeed, a slight increase is noticeable both at the surface level (0–3 cm) and subsurface (3–10 cm) (Figure 4f).

In contrast to Macay (Figure 4), the results for Salloc indicate that both surface alkalinity levels (0–3 cm) and subsurface alkalinity levels (3–10 cm), estimated from pH, exhibit a slight reduction on burned surfaces compared to unburned surfaces (Figure 5a). Similarly to Macay, EC levels (0–3 cm) for Salloc on burned surfaces show a slight increase persisting up to a year later compared to unburned surfaces, which can also be characterized as slightly saline or salt-free. Additionally, EC levels for depths between 3 and 10 cm also exhibit a slight increase during the 2022–2023 period for Salloc (Figure 5b). Organic matter (OM) at the surface level (0–3 cm) of burned surfaces demonstrates a predominant increase (during the T1–T3 period) when compared with unburned surfaces throughout the year. Although less pronounced, these changes are also observed when OM at a depth of 3–10 cm is analyzed (during the T1–T4 period) for the community of Salloc (Figure 5c). A pattern

similar to that of OM is observed when nitrogen (N), phosphorus (P), and potassium (K) are analyzed at the surface level (0–3 cm) and subsurface (3–10 cm) (Figure 5d–f). However, none of the changes detected in pH levels, organic matter, electrical conductivity, phosphorus, nitrogen, and potassium are statistically significant.

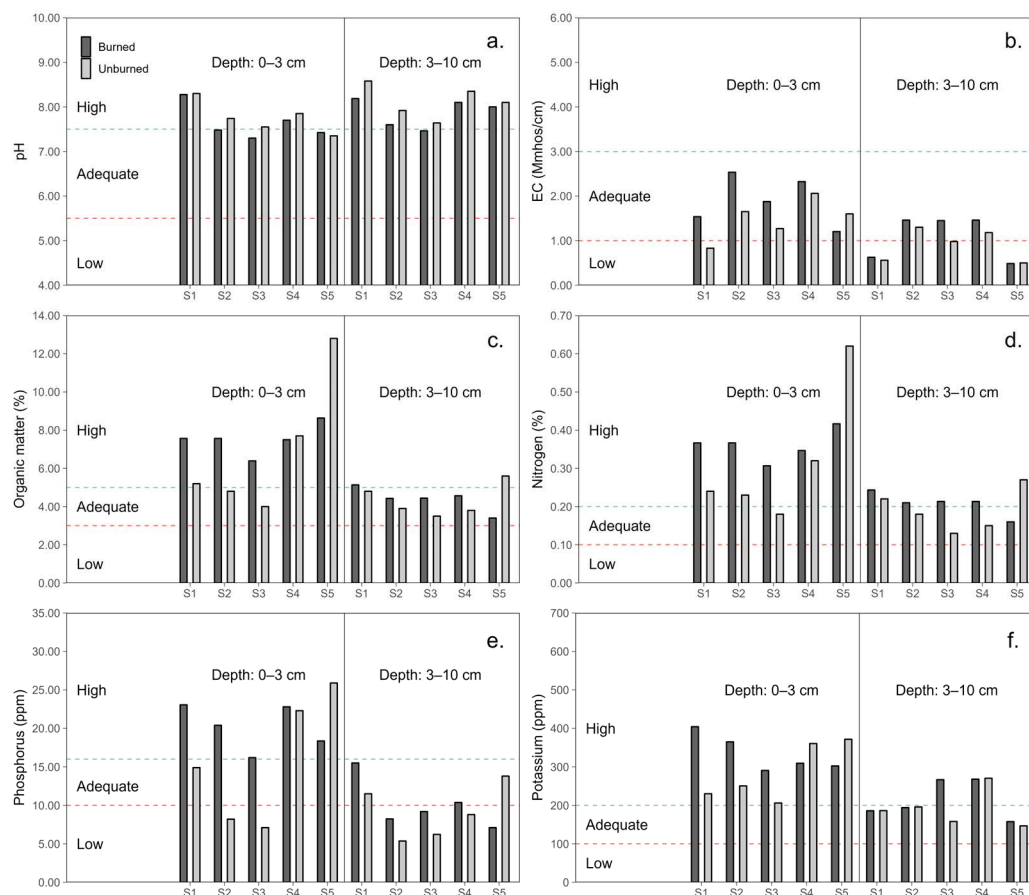


Figure 5. Variations in (a) pH, (b) electrical conductivity, (c) organic matter, (d) nitrogen, (e) phosphorus, and (f) potassium properties at depths of 0–3 cm and 3–10 cm in the community of Salloc. The climatic seasonal periods associated with the samples (S1, S2, S3, S4, and S5) are detailed in Figure 2. Thresholds (high, adequate, low) linked to soil fertility in the Andean region [79] are also graphed.

To propose a fertility interpretation linked to unburned and burned areas for the communities of Macay and Salloc (Figures 4 and 5), thresholds related to conditions of greater or lesser fertility in soils intended for the production of Andean cultivated pastures and natural pasture were considered [79]. At both surface and subsurface levels (up to 10 cm deep), in both burned and unburned areas, properties such as pH, organic matter, nitrogen, and potassium would exhibit values close to adequate levels that contribute to soil fertility for much of the year in the community of Macay (Figure 4). However, electrical conductivity and phosphorus do not predominantly present favorable fertility conditions when a depth of 3–10 cm is analyzed (Figure 4b–e); indeed, an increase to adequate levels for fertility conditions is only detected when the surface level (0–3 cm) is analyzed. Similar patterns in pH, organic matter, nitrogen, and potassium, as well as electrical conductivity and phosphorus values, are also observed for Salloc (Figure 5a–f).

At a more superficial level (0–3 cm), higher values of soil properties are observed in unburned areas compared to burned areas during T4 (one year after the fire) in Salloc (Figure 5). However, this pattern is not observed in Macay (Figure 4). This discrepancy may be due to the slight slope of the terrain in Salloc, which limits surface drainage during the rainy season, compared to Macay, where the slope is steeper (Table 1, Figure 3). Finally,

it is worth mentioning that the soil texture in our study areas was characterized as sandy loam between periods T1 and T4.

3.4. Performance of Dry Biomass

The herbaceous species (exotic, native, or endemic) identified in both burned and unburned areas for the communities of Macay and Salloc are described in Table S1. The vegetation of this herbaceous grassland comprises a variety of plants and grasses [80,81] (Table S1). The performance of dry biomass for Macay and Salloc (in grams per square meter) after the wildfire is detailed in Table 4. For comparison, both burned and unburned sites were analyzed for both communities. Our results indicate a reduction in the performance of dry biomass one year later (Table 4).

Table 4. Biomass estimated (g/m²) for both burned and unburned sites in both communities between 2022 and 2023.

Peasant Community	Macay		Macay		Salloc	
	g/m ²	Number of Plant Species	g/m ²	Number of Plant Species	g/m ²	Number of Plant Species
Unburned area 2020	307	10	286	10	154	10
Burned area 2023	240	18	112	13	98	13

On average, the biomass in burned areas is reduced to 30.1% of the biomass in unburned areas in Macay (an approximate reduction of the fuel load of around 206 g/m²). A similar pattern is observed in Salloc, where the biomass over burned areas is reduced to 46% of the biomass in unburned areas between 2022 and 2023 (an approximate reduction of fuel load of around 171 g/m²) (Table 4). In contrast, an increase in the number of herbaceous plant species in burned areas relative to unburned areas was identified in both Macay and Salloc (Table S1).

To evaluate a longer period of vegetation recovery, a wildfire that occurred in Macay in 2020 in a similar ecosystem was also considered. Burned and unburned areas were selected and compared. Our results indicate vegetation recovery of up to 78%, relative to unburned areas, three years after the wildfire in 2020 (Table 4).

Precipitation between October and December 2022 was lower than in other years (Figure 2), indicating a delay in the onset of the rainy season during the 2022–2023 period (October–November). Our results indicate that the rainy season lasted until May, but rainfall was well below average between January and April.

The Shannon Diversity Index results indicate mainly that the burned area in Macay shows slightly greater species richness than the unburned area, which presents low diversity (Table 5). In contrast, the fire did not affect species richness in Salloc (Table 5).

Table 5. Shannon Diversity Index estimated for Macay and Salloc for unburned and burned areas.

Shannon Diversity Index		Macay	Salloc
Unburned area	Transect a	1.772	1.541
	Transect b	1.338	1.338
Burned area	Transect c	2.294	1.428
	Transect d	2.036	1.567

4. Discussion

Soil properties such as pH, electrical conductivity (EC), organic matter (OM), nitrogen (N), phosphorus (P), and potassium (K) in Macay and Salloc (except for pH in Salloc) exhibit a slight increase between the onset and culmination of the rainy season because of several factors. One contributing factor is the formation of ash and combustion residues, which may contain alkaline substances such as carbonates and oxides, thereby causing pH levels to rise [82,83]. The authors note that another factor contributing to pH increases could be the severity of the wildfire. However, grasslands or shrublands typically exhibit low to moderate fuel loads, leading to potential fire activity of relatively moderate severity compared to fire that occurs in forest ecosystems with a high fuel load [83].

Given the low fuel load of the grasslands, our results show that the wildfires that occurred in the communities of Macay and Salloc were mainly characterized by low to moderate levels of severity. Therefore, this suggests the contribution of ash from the wildfire at the surface level of the soil. It is essential to recognize that this varies depending on soil depth and the severity of the fire, as pH levels can experience a significant increase [84]. Indeed, our results are more sensitive to changes at the surface level (3 cm) than the subsurface level (10 cm). Our pH values are consistent with studies conducted by Huaman [85] and Alva and Manosalva [86] in central and northern Peru, respectively.

EC levels are high in burned areas following a fire because of the release of soluble inorganic ions from burned soil organic matter and the incorporation of ash into the soil [13,87–89]. It is possible that the presence of base cations in the ash, such as calcium, magnesium, and potassium, has also contributed to an elevation in EC [90]. Our findings suggest that the increase in EC is a result of the incorporation of ash between the onset and culmination of the rainy season, but EC subsequently returns to values more similar to those observed in unburned areas. Therefore, these alterations would be temporary, as the salts incorporated into the soil quickly diminish due to rainfall and runoff during the rainy period [91]. Soil EC levels that are excessively high or low can limit crop growth [92], but the EC values estimated in the soil after the wildfire suggest low salt conditions, consistent with studies conducted by Huaman [85] and Pacheco [93] in central and southern Peru, respectively.

The impact of fire on soil properties is typically contingent upon factors such as intensity, duration, and frequency of the fire, which collectively constitute wildfire severity [26,31]. Very severe wildfires can lead to a decrease in organic matter compared to initial values, resulting in soil degradation [94]. However, a notable increase in organic matter can also be observed in the surface levels of the soil after a fire. This increase can enhance both the quantity and quality of grassland production throughout the year [95]. Organic matter levels in this study were also found to be higher in burned areas than in unburned areas. This is consistent with comments from people interviewed in our study who said burning can improve soil fertility. Our findings align with results obtained by Alva and Manosalva [86] in northern Peru.

In the medium term (1–5 years), fire impacts on perennial forests, different aged forests, and pastures in the tropical Andes can be characterized by a decrease in the availability of N, P, and K [96]. The results for N, P, and K in this study indicate that wildfires did not have a negative effect on the physicochemical properties of the soils, and soil quality remained unaltered a year post-fire. This could be attributed to the potentially low severity of wildfires because of minimal fuel loading from grasslands. For example, temperatures not exceeding 400 °C (estimated from experimental fire) can increase nitrogen levels [97]. This notable increase in nitrogen can mitigate the impact of leaching and subsequent drainage by rainfall, which may otherwise result in a nitrogen deficit in the soil. Meanwhile, an increase in phosphorus in burned areas compared to unburned areas was identified after the wildfire, possibly as an impact of the wildfire. Mineralization of organic phosphorus, along with the presence of ash derived from vegetation combustion, can also influence this process [11,82]. These elements have a beneficial impact on the soil, improving its fertility through the properties of ash [98].

Fire can cause a change in potassium (K) content in Peruvian Andean ecosystems. For example, Pacheco [93] suggests a potential decrease in potassium of around 25%; however, its classification level remains unchanged, as it remains above the optimal level. Non-significant changes in potassium are also documented by Alva and Manosalva [86]. Nonetheless, our study observed an increase in potassium levels in the burned areas of both communities, which is consistent with findings from studies conducted in other regions of Peru [85,99].

Land use change and human-induced fires have transformed landscapes [25], but the most traditional and modern human uses of fire typically do not have significant direct impacts on soils in areas with low fuel loads. There is uncertainty about the impacts of wildfire on soil properties, as different fuel loads (forest, shrubland, or grass) and other factors can play specific roles. Despite the common occurrence of wildfires in Andean countries, relatively little is known about the short-term impact of wildfires on grasslands. Moreover, fire can induce substantial soil alteration through indirect effects, including changes in vegetation restoration [96]. In this study, at the end of the dry period in 2023, both communities in Cusco exhibited adequate levels of nutrients for plant development. In addition, the delay in the start of the rainy season does not suggest significant soil leaching processes between September and November.

Despite some temporal variations in soil properties at the most superficial level (0–3 cm) and the documented objective of burning by peasant communities to improve soil fertility (as stated in interviews), seasonal changes in the physical and chemical properties of soils do not suggest that grassland burning makes a substantial positive and prolonged contribution to soil fertility in our study area. Optimal soil fertility conditions typically support healthy plant growth and development, leading to greater productivity [100]. Nevertheless, wildfires in grassland ecosystems can serve other purposes, such as stimulating the regeneration of specific plant species, maintaining diversity, or acting as a tool for reclaiming encroached grasslands [26,101]. Indeed, one-year post-fire suggests that wildfires stimulated the growth of other herbaceous species in Cusco. Our findings in the community of Macay indicate that the areas affected by the fire presented greater species richness than areas not affected by the fire. This is consistent with the study carried out in Peru by De la Cruz and Condor [11]. In contrast, species richness diversity remains low in burned and unburned areas in Salloc. This suggests that environmental variability linked to the different elevations or slopes can play an important role in the presence and abundance of Andean vegetation species [102].

Overall, results are consistent with the comments from individuals interviewed across the study areas, who anticipate varying responses from the grasslands, in terms of both quantity and quality, in the coming months because of burning practices [16,17]. Our findings also indicate vegetation recovery of up to 78% approximately three years after the wildfire. This aligns closely with the grassland recovery timeframe (1–4 years) reported by the local population during the interviews.

The multifaceted nature of wildfires, which encompasses climate-sensitive hazards and social, economic, and political factors, often complicates stakeholder efforts to reach a common understanding of how to address the problem and propose adequate solutions [103]. Current international governmental strategies are oriented towards adopting prevention measures and establishing control plans that include initiatives for impact mitigation training, and alternative methods to reduce fuel load by prescribed burns [104]. In Peru, however, existing measures are predominantly punitive, encompassing both imprisonment and significant monetary fines [48,49], with a focus on short-term reactive management once a fire occurs. This reactive approach involves actions such as hiring personnel, procuring equipment to respond to wildfire emergencies, and providing fire-fighting training. Implementing policies in Peru that incorporate the use of fire by farming communities represents a significant challenge for decision-makers [46,105]. Furthermore, there exists a wide range of sectoral, disciplinary, and personal perspectives among those involved in the different stages of wildfire management, who have yet to find a coordinated

space for joint action. Further research is needed in Peru to understand how people use fire (controlled burns or prescribed fire) and what role the institutions involved should play [17,46].

The Intergovernmental Panel on Climate Change (IPCC) has projected that by the end of this century, temperatures in tropical regions could potentially increase by up to 4.8 °C [106]. This underscores the importance of implementing appropriate measures and strategies in the management of fire use, known as corrective management, instead of solely prioritizing wildfire management, which involves both prospective and reactive approaches, by government authorities in Peru. The concepts of corrective, prospective, and reactive management of disaster risk are documented in Peruvian law under SINAGERD [82].

5. Conclusions

This study analyzed the effects of fire on soil properties in herbaceous grasslands and its social context in Cusco, in southern Peru. Two wildfires that occurred in grasslands during 2022 in two peasant communities in Cusco were studied. Andean grassland ecosystems are fragile environments facing significant threats, necessitating better management strategies. The results indicate that the values of various soil properties initially increased after the fire, between the second and third seasons of analysis (the beginning of the rainy season and the rainy season), then showed a gradual reduction, mainly due to associated factors such as rainfall and runoff contributing to the leaching process. The values of electrical conductivity, organic matter, and NPK continued to increase in the four seasons due to the incorporation of ash into the soil resulting from the wildfires. Our findings suggest that changes in soil properties could be linked to diverse vegetation, physical, and climate factors. It is important to note that factors such as fuel load and fire severity level can play an important role in changes in soil properties [107]. The low fuel load from grasslands in the Peruvian Andes may have contributed to the stimulation of regeneration of other herbaceous species after the rainy season, which has also been described in other investigations [26,101]. Another highlight is that the load of vegetative fuel from the Andean grasslands after burning will fully recover within 4 years. Similar findings are also documented in central Peru by De la Cruz and Condor [11]. This timeframe was also described by the local population during the interviews.

Given local people's burning practices and interests, research is needed to compare burn severities through controlled burns on grasslands. This should be approached cautiously, as fire behavior and combustion dynamics may modulate burn severity differently (whether it involves grassland fuels or other fuels). Our results can help decision-makers formulate policies, regulations, and proposals for reducing wildfire impacts, as well as for restoring vegetation in the Andean region of Cusco, which is an important international tourism destination.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/fire7070259/s1>, Table S1: Description of the herbaceous species identified in both burned (burn) and unburned (unb) areas for the Macay and Salloc communities.

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