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

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Abstract: The soils represent a valuable renewable resource on human timescales and interact with distinctive grassland ecosystems characterized by their elevated biodiversity and essential provision of ecosystem services, such as water supply and carbon sequestration. However, knowledge concerning the effects of wildfires on soil properties and nutrient availability remains limited in the Andes. Andean grasslands currently stand as ecosystems most affected by wildfires in the Peruvian Andes. Our objective is to analyze the effect of fire activity on soil physicochemical properties and analyze its social context in Cusco, situated in the southern Andes of Peru. Five soil samples were collected during both the dry and rainy seasons to characterize changes in soil properties. Additionally, the vegetation restored after the wildfire was analyzed. Changes in soil properties subsequent to the fire 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 the seasonal rainfall and runoff regime contributing to the leaching process. Our findings suggest that the complete regeneration of vegetation following a wildfire may require approximately four to five years. This assertion is supported by the perceptions of the affected population, as revealed through interviews conducted within two local farming communities. These results hold significance for decision-makers in formulating policies and regulations regarding grasslands and their seasonal restoration.

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

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1. Introduction

The Andes region in South America harbors one of the most biodiverse montane ecosystems globally [1,2]. The tropical Andean plant diversity is remarkably vast, and their habitat types are interconnected [3,4]. Grassland and shrubland communities at high elevations predominate in the Andean mountains [5,6]. The high Andean grasslands represent distinct ecosystems characterized by their high biodiversity and essential provision of ecosystem services [7]. These ecosystems are fragile environments facing significant threats characterized by marked climatic conditions and variable food sources for grazing [8]. Wildfires can also significantly impact the chemical, physical, and biological properties of soil due to their duration and intensity of burn [9]. Indeed, soil plays a crucial role in supporting plant growth through nutrient cycling, mineral storage, and carbon sequestration

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[10,11]. Degradation of the biological, chemical, and physical properties of forest soils can temporarily or permanently limit the capacity for plant growth, suggesting that immediate fire impacts are concentrated on the surface soil horizon [12]. The soils in these ecosystems sustain the grasslands, which serve as the primary food source for livestock. Andean grasslands are currently the ecosystems most affected (80%) by wildfires in the Peruvian Andes during the second half of the year [13]. Where the role of the population in the Peruvian Andes is undeniable, as grassland fires are often attributed to human activity [14,15]. Grasslands play a vital role in livestock production as an economic activity in Peru, where there is the world's largest population of Alpacas, with around 4.5 million, comprising about 85% of the total population [16]. However, fire activity in the context of climate change could limit vegetation succession by influencing the compositions of plant communities and soil properties [6,17].

A prescribed fire is the deliberate use of low-intensity fire in various countries to achieve diverse objectives, contingent upon factors such as climate conditions, forest fuel, and topography [18–21]. However, fire activity clearly alters the environment, including its 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 intensity and severity are low [22]. For instance, a study conducted in Spain documented negative impacts (50%) on the chemical and physical properties of forest soil up to nine years later, with some exceptions such as soil texture and invertebrate biomass [11,23]. In contrast, a study in Brazil conducted by [24] reported that fire increased chemical properties while decreasing potential acidity and phosphorus content in the soil, with no observed alteration in soil physical properties due to the wildfire.

In this context, the impact of fire on soil properties can be relative, yielding significantly different outcomes based on biological, chemical, and physical factors. The extent of soil disturbance by wildfire depends on various factors including fire intensity, duration, recurrence, forest fuel load, and soil characteristics. This variability is evident in studies conducted across different regions such as the USA [20,25], Europe [16,19,26–29], and Asia [30,31 among others. The impact of burning and grazing on Paramo soils may primarily affect physical characteristics, and variations in chemical properties may not necessarily translate into differences in vegetation structure between grazed, burned, and undisturbed sites [12]. Nevertheless, clear shifts in the relative abundance of plant growth forms have been documented [32]. Additionally, while the recovery of certain soil properties and processes through reforestation may facilitate the restoration of native forests to conditions similar to those prior to wildfire occurrence, this process remains context-dependent [33].

In general, high-, medium-, and low-severity fire activities can occur when vegetation is affected by a wildfire or controlled burning practice. In this paper, the term "wildfire" is used to describe any unplanned and uncontrolled fire that starts in grasslands due to burning practices. Low-severity fire activities, such as controlled burns, could have positive effects by accumulating organic matter in the soil due to the incomplete combustion of biomass [34]. However, ashes produced during wildfires resulting from burns could also impact soil properties [35,36].

To predict fires and limit their impacts, new knowledge is needed about fire activity and the spatial and temporal distribution of factors affecting its occurrence. This is of utmost importance for agroforestry management and to reduce environmental degradation [37]. Nevertheless, wildfire impacts 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.

2. Materials and Methods

2.1 Study Area

Cusco is the historical capital of Peru, situated in southern Peru (13°31′20″S 71°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 [38]. The Cusco region boasts altitudes

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reaching up to 6,300 meters above sea level (asl), with a mean altitude of 3,400 meters asl (Figure 1a). This area of Peru displays a significant variation in annual precipitation levels, with the northwestern part experiencing the highest accumulation (5000-8000 mm/year) in the Amazon region, while the southern zone receives the lowest annual rainfall (200-1000 mm/year) in the Andean region [39]. Grassland ecosystems between 3000 and 4400 meters above sea level (masl) are predominant in the Andean mountains of Cusco [40]. Cusco is one of the region's most severely affected by wildfire emergencies in Peru [13], and has witnessed a significant increase (250%) in the occurrence of wildfires during extreme drought periods such as those in 2005 and 2010 [41,42]. Moreover, the COVID-19 pandemic played a role in the increased occurrence of wildfires during 2020 due to migration processes from urban to agricultural activities [15].

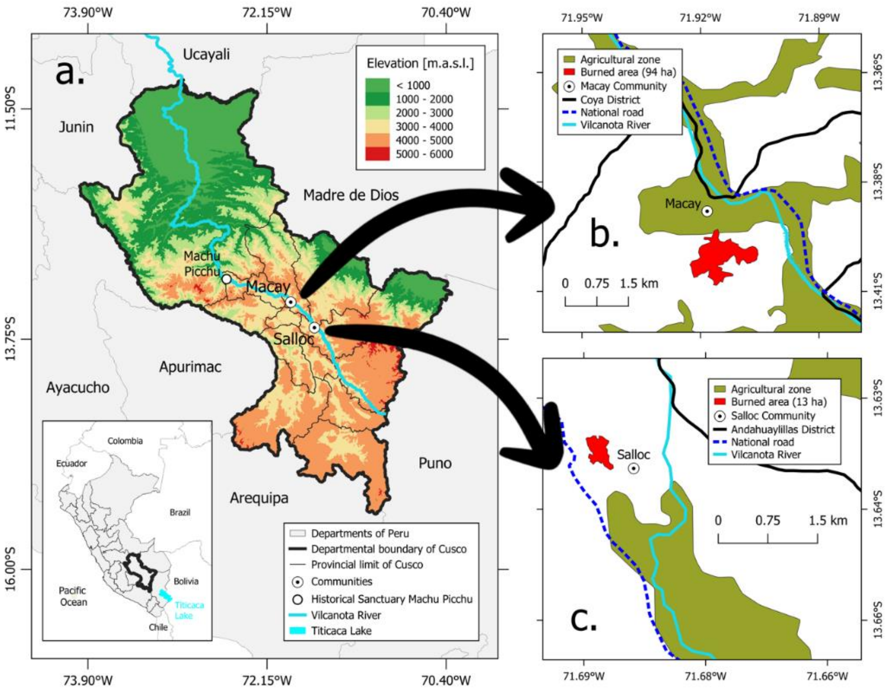

Figure 1. The location map delineates the study areas designated for the monitoring of soil properties and conducting interviews within the (a), Macay (b), and Salloc (c) communities of Cusco.

A recent study of fire activity conducted in the mountainous region of Cusco reveals that only 4% of documented fire incidents are classified as wildfires emergencies, while unauthorized burning practices account for the remaining 96% [43]. Consequently, the dynamic of fire activity in Cusco is significantly influenced by burning practices associated with agriculture and livestock [15]. Furthermore, their frequency appears to be influenced by climate oscillations such as droughts [13]. The study was conducted in the Calca and Quispicanchis provinces, specifically in the Macay and Salloc farmer communities of Cusco, respectively (see Figure 1bc). 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 Civil Defense National Institute (INDECI-Peru).

Table 1. Study area and wildfire emergencies characteristics.

Characteristics	Zone 01	Zone 02
Farmer community	Macay	Salloc
Province	Calca	Quispicanchi
District	Calca	Andahuaylillas
Altitude	2944 m asl.	3524 m asl.
Temperature	10° - 25 °	5° - 9°

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Main economy activity	Agriculture (potatoe, corn etc.), Livestock (cattle and sheep)	Agriculture (corn etc.), Livestock (cattle and sheep)

Characteristics	Wildfire	Wildfire
Approximate duration	15:00 - 19: 00 hrs.	14:30 - 18:00 hrs.
Date	Aug 23, 2022	Aug 30, 2022
Affected area	94 ha	13 Ha
Affected Vegetation	Grassland	Grassland

To establish a connection between this study´s findings an the local population perceptions, a set of interviews was conducted with residents from the communities of Macay (10 interviews) and Salloc (10 interviews) between the fire season (August to December) of 2023. The interviews were conducted with individuals ranging in age from 22 to 70 years old, all of whom were engaged in agriculture, with 90% being women and 10% men. Throughout the interviews, experiences related to burning and wildfires were collected, as all interviewees either had personal experience with conducting burns or had been affected by a wildfire.

2.2. Soil Physico-Chemical Properties Analyses

To assess the impact of fire on soil physico-chemical properties, samples were collected from zones 01 and 02 (Macay and Salloc) (see Figure 1, Table 1). Soil sampling was conducted at five different time points: S1, S2, S3, S4, and S5, corresponding to the dry season (T1), onset of the rainy season (T2), rainy season (T3), and subsequent dry season (T4) (Figure 2). Priority was given to samples representing seasonal periods such as the dry season (May-September), rainy season onset (October- December), and rainy season (January-April) [41]. Subsamples were collected from both burned and unburned plots on September 04-07, December 04-05, March 04-05, June 01-02, and August 29-30 (Figure 2). This selection was made due to 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 [44], leading to soil erosive processes in this ecosystem type [45].

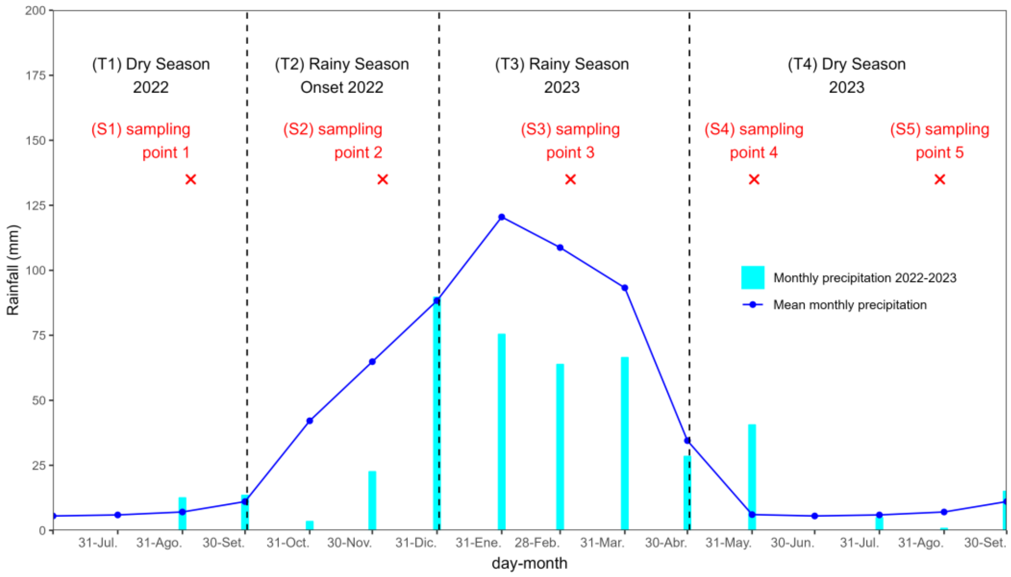

Figure 2. Rainfall pattern 2022-2023 and sampling (S1, S2, S3, S4, S5) of soil properties of Cusco performed during dry season (T1), Rainy season onset (T2), Rainy season (T3) and Dry season (T4).

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To maintain sample consistency and minimize potential variations that could affect the results, two depths, at 3 and 10 centimeters, were considered when extracting subsamples from both Macay and Salloc. This approach aligns with the method proposed by [12]. 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 Cusco University (San Antonio Abad National University).

Soil texture was determined using the hydrometer method [46], while soil pH was measured with a pH meter following standard procedures [47]. Soil nitrogen concentration (N) (%) was assessed using the Micro-Kjeldahl method [48], and soil organic matter (OM) (%) was determined using the Walkley and Black method [49]. Potassium (K) (ppm) was estimated using the NH4 method [50], while soil available phosphorus (P) (ppm) was determined using the modified Olsen method [51]. Additionally, electrical conductivity (mmhos/cm) (EC) was evaluated using a conductivity meter.

2.3. Biomass Estimation

The modified K.W. Parker method [52], known as the "Step transect," involves collecting samples along a transect [53]. In this transect, 100 observations were conducted, with triple steps taken, recording the types of plants and vegetation cover. This documentation was carried out in both the burned and unburned areas of the Macay and Salloc communities. In the center of each transect, a $1m^2$ quadrant was randomly established, and the vegetation was cut and placed in paper bags. Biomass was determined using the destructive harvesting method [54]. Subsequently, dry matter was obtained by drying the samples in an oven at a temperature of 60°C for 48 hours, following the gravimetric method, 60°C x 48 h [55]. 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. This diversity encompasses the array of plant species within a specific locale [56].

2.4. Statistical Analysis

Previously, an exploratory data analysis was conducted to assess the data distribution and identify outliers. No outliers were detected, nonetheless, the data did not exhibit a normal distribution. Therefore, non-parametric statistics were 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 employed [57]. This non-parametric test was utilized to compare the medians of two independent samples and ascertain whether they are equal. A significance level of 0.05 was employed for all analyses using the R software.

3. Results

3.1. Perception of Population

Regarding the population's perceptions, two primary reasons for utilizing fire are expressed: a) clearing land to expand agricultural areas (eliminating weeds and stubble), and b) rejuvenating grasslands during the latter part of the year. Burnings are typically organized by smaller community groups, assuming the primary coordinating role. Additionally, there exists a consensus among the populace that burning contributes to the enhancement of fertility in uncultivated soils. However, despite this, it is noted that the time required for complete recovery of grasslands after burning or wildfire can vary between 1 and 4 years. A brief overview of interviews is presented in Table 2.

Table 2. Synthesis of social perspectives and perceptions gathered from interviews conducted throughout around Macay and Salloc, during the 2023 fire season.

Question	Social opinion
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, September (for preparing the ground for the next agricultural campaign). April, May, October, November (for grassland renewal purposes).
Who is involved in the burning process	Families take responsibility for managing the fire to prevent its spread, along with personnel possessing expertise in burning practices.
Does the burning of grasslands contribute to soil fertility improvement?	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 1 to 4 years after the fire.

3.2. Changes of Soil Properties

Figures 3 and 4 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 the Macay and Salloc communities 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 (Figure 3 and 4). For example, the results for the Macay community 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 3a). 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 3a). 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 3a).

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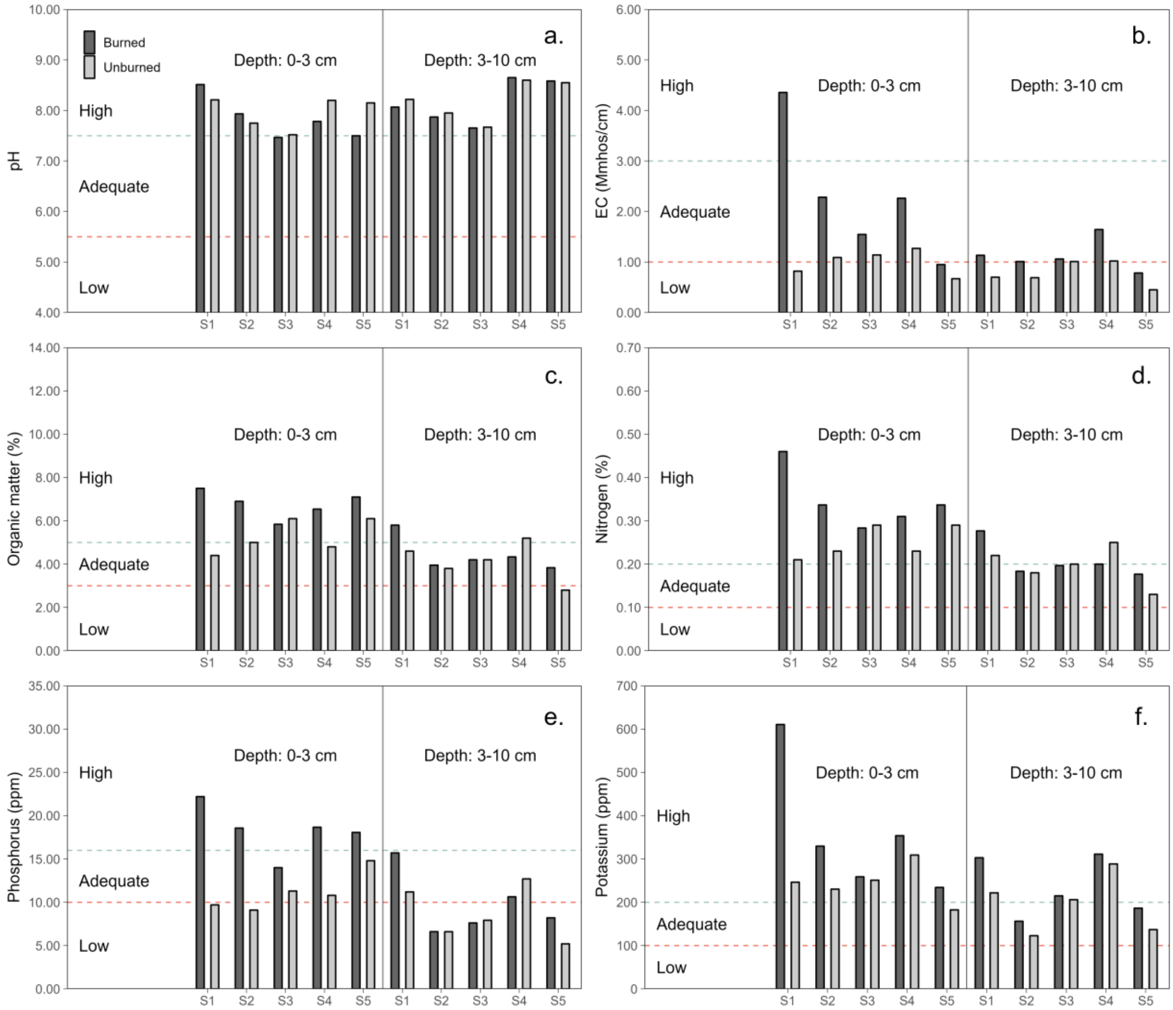

Figure 3. Variations in pH, electrical conductivity, organic matter, nitrogen, phosphorus, and potassium properties at depths of 0-3 cm and 3-10 cm in the Macay community. The climatic seasonal periods associated with the samples (S1, S2, S3, S4, and S5) are detailed in Figure 2.".

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 predominant changes (Figure 3b). 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 3c). A comparable pattern to 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 3d, 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 3f).

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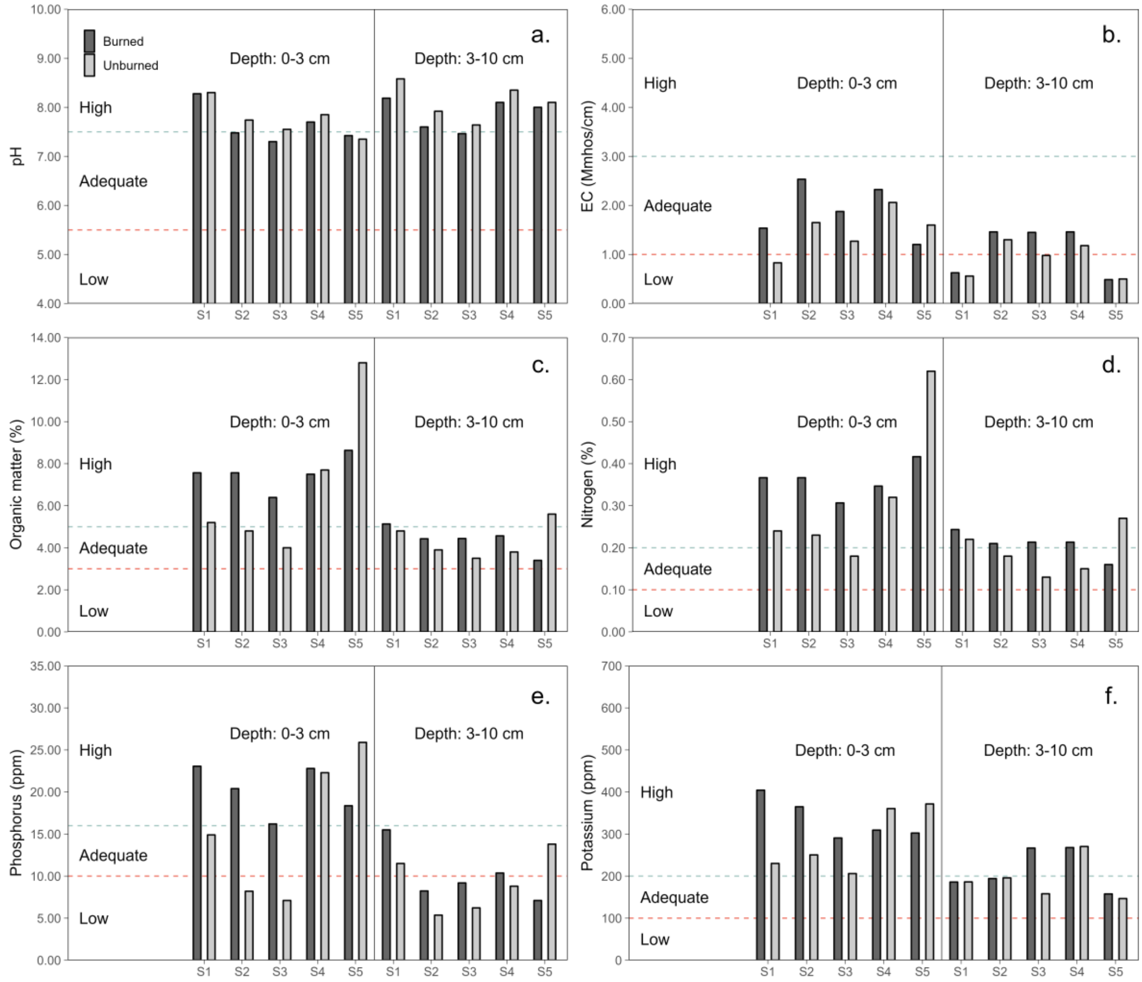

Figure 4. Variations in pH, electrical conductivity, organic matter, nitrogen, phosphorus, and potassium properties at depths of 0-3 cm and 3-10 cm in the Salloc community. The climatic seasonal periods associated with the samples (S1, S2, S3, S4, and S5) are detailed in Figure 2.".

In contrast to the Macay community (Figure 3), the results for the Salloc community 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 4a). Similarly to the Macay community, EC levels (0-3 cm) for the Salloc community 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 the Salloc community (Figure 4b). Organic matter (OM) at the surface level (0-3 cm) of burned surfaces demonstrates a predominant increase (except T4 and T5) 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 (except T5) for the Salloc community (Figure 4c). A similar pattern to 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 4d, e, f). However, all changes detected in pH levels, organic matter, electrical conductivity, phosphorus, nitrogen, and potassium are not statistically significant.

To propose a fertility interpretation linked to unburned and burned areas for the Macay and Salloc communities (Figures 3 and 4), thresholds related to conditions of greater or lesser fertility in soils intended for the production of Andean cultivated pastures and natural pasture were considered [58]. At both surface and subsurface levels (0-10 cm), 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 Macay Community (Figure 3). However,

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electrical conductivity and phosphorus do not predominantly present favorable fertility conditions when a depth of 3-10 cm is analyzed (Figure 3b, e); indeed, an increase to adequate levels for fertility conditions is only detected when the surface level (0-3 cm) is analyzed. Moreover, similar patterns identified in pH, organic matter, nitrogen, and potassium, as well as electrical conductivity and phosphorus values are also observed for the Salloc community (Figure 4).

Table 3. Description of the herbaceous species identified in both burned (burn) and unburned (unb) areas for the Macay and Salloc communities.

Family	Genus - herbaceous species	Local name	Growth and duration	Macay		Salloc	
				Unb	burn	Unb	burn
Poaceae	Melinis minutiflora	Pasto gordura	Herbaceous/perennial	x	x	x	x
	Stipa ichu	Paja brava	Herbaceous/perennial		x	x	x
	Poa annua	Qachu	Herbaceous/annual	x	x		
	Muhlenbergia fastigiata	Grama dulce	Herbaceous/perennial		x		
	Calamagrostis intermedia	Cebadilla	Herbaceous/annual	x	x		
	Pennicetum clandestinum	Kikuyo	Herbaceous/perennial			x	x
	Paspalum vaginatum	Grama	Herbaceous/perennial			x	x
	Dactylis glomerata	Eno pasto	Herbaceous/perennial			x	x
Asteraceae	Taraxacum officinale	Diente de león	Herbaceous/perennial		x		
	Tagetes elliptica	chicchinpa	Herbaceous/perennial	x	x		
	Schkuria pinnata	Canchalagua	Herbaceous/annual		x	x	x
	Viguiera lanceolata	Sunchu	Herbaceous/perennial	x	x	x	x
	Laggera crispata	-	Herbaceous/annual		x		
Cactaceae	Austrocylindropuntiae subulata	Pata kiska	Herbaceous/annual	x	x		x
	Opuntia ficus	Airampo	Shrub/perennial	x			
Lamiaceae	Salvia rosmarinus	Romero	Herbaceous/perennial		x		
Dennstaedtiaceae	Pteridium aquilinum	Rakiraki	Fern/perennial	x			
Berberidoideae	Berberis vulgaris	Checche	Shrub/perennial		x		
Equisetaceae	Equisetum arvense	Cola de caballo	Shrub/perennial	x			

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Geraniaceae	Erodium cicutarium	Aguja de pastor	Herbaceous/perennial		x		
Pteridaceae	Adiantum capillus	Culantrillo	Fern/perennial		x		
Euphorbiaceae	Euphorbia prostata	Mullaca	Herbaceous/annual		x		
Verbenaceae	Verbena officinalis	verbena	Herbaceous/perennial		x		x
Anacardiaceae	Schinus molle	Molle	Shrub/perennial	x	x		
Amaranthaceae	Altermanthera pungens	Illutu illutu	Herbaceous/perennial			x	x
Convolvulaceae	Dichondra sericea	Oreja de ratón	Herbaceous/perennial				x
Brassicaceae	Brassica rapa	Lávanos	Herbaceous/annual			x	x
Fabaceae	Trifolium repens	Trébol	Herbaceous/perennial			x	x

3.3. Performance of Dry Biomass

The herbaceous species identified in both burned and unburned areas for the Macay and Salloc communities are described in Table 3. The vegetation of this herbaceous grassland comprises a variety of plants and grasses (Table 3). The performance of dry biomass for the Macay and Salloc communities (in grams per square meter) after the wildfire is detailed in Table 4. For comparison purposes, both burned and unburned sites were analyzed for both communities. Our results indicate a reduction in the performance of dry biomass (Table 4). On average, the biomass over burned areas is reduced to 30.1% compared to unburned areas in the Macay community. A similar pattern is observed in the Salloc community, where the biomass over burned areas is reduced to 46% compared to unburned areas between 2022 and 2023 (Table 4). In contrast, an increase in the number of herbaceous plant species in burned areas relative to unburned areas was identified in both the Macay and Salloc communities (Table 3).

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

On the other hand, the 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; however, rainfall was well below average between January and April."

4. Discussion

Soil properties such as pH, electrical conductivity (EC), organic matter (OM), nitrogen (N), phosphorus (P), and potassium (K) in the Macay and Salloc communities (except for pH in Salloc) exhibit a predominant slight increase between the onset and culmination of the rainy season due to 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 [59,60]. Additionally, the authors note that another factor contributing to pH increases could be the high intensity of the wildfire. However, grasslands or shrublands typically exhibit low-to-moderate fuel loads, leading to wildfires of relatively moderate intensity and resulting in moderate burn severity compared to wildfires (Sanchez-Garcia et al., 2023). It is essential to recognize that this varies depending on the depth and intensity of the fire, as pH levels can experience a significant increase [61]. Indeed, our results are more sensitive to changes at the surface level than at the subsurface

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level. Our pH values are consistent with studies conducted by [62] and [63] in central and northern Peru, respectively.

EC levels are higher in burned areas compared to unburned areas following a fire, attributed to the release of soluble inorganic ions from burned soil organic matter and the incorporation of ash into the soil [11,64–66]. Consequently, the presence of base cations in the ash, such as calcium, magnesium, and potassium, could also contribute to an elevation in EC [67]. 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, yet EC subsequently returns to values more similar to those observed in unburned areas. These alterations are temporary, as the salts incorporated into the soil quickly diminish due to rainfall and runoff during the rainy period [68]. Soil EC levels that are excessively high or low can limit crop growth [69], however, the EC values estimated in the soil after the wildfire suggest low salt conditions, consistent with studies conducted by [62] and [70] in central and southern Peru, respectively.

The impact of fire on soil properties is typically contingent upon factors such as intensity, duration, and frequency, collectively constituting wildfire severity [23,28]. The effects of very intense wildfires can lead to a decrease in organic matter compared to initial values, resulting in soil degradation [71]. 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 grassland production in terms of both quantity and quality throughout the year, while also allowing for the estimation of reserves of nitrogen, phosphorus, and potassium [72]. In contrast, organic matter levels in this study were found to be higher in burned areas compared to unburned areas. Our findings align with results obtained by [63] in northern Peru.

In some cases, the availability of N, P, and K has been observed to decrease in the medium term (0–5 years) in Andean regions [73]. Despite the common occurrence of wildfires in these areas, relatively little is known about the short-term impact of wildfires on grasslands. 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, thus maintaining the unaltered soil quality. This could be attributed to the potentially low severity of the wildfires resulting from minimal fuel loading from the grasslands. For instance, nitrogen levels increase after wildfires when temperatures do not exceed 400°C [74]. 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. An increase in phosphorus in burned areas compared to unburned areas was identified after the wildfire, possibly due to fire intensity, as elevated temperatures can trigger the mineralization of organic phosphorus, and the presence of ash derived from vegetation combustion can also influence this process [9,59]. These elements have a beneficial impact on the soil, improving its fertility through the properties of ash [75].

The increase in potassium (K) is typically attributed to burning or fires due to the accumulation of ash produced during the combustion of vegetation. Conversely, [70] suggests a potential decrease in potassium, around 25%; however, its classification level remains unchanged as it remains above the optimal level. An increase in potassium was observed in both communities in the burned areas in this study, consistent with studies conducted in Peru by [62,63] and [76].

Land use change and human-induced fires have transformed landscapes [22], however, the most traditional and modern human uses of fire typically do not have significant direct impacts on soils in areas with low fuel loads. Fire can induce substantial soil alteration through indirect effects, including changes in vegetation restoration [73]. For instance, at the end of the dry period in 2022, both communities in Cusco exhibited adequate levels of nutrients for plant development. 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 farmer communities to improve soil fertility through interviews, seasonal changes in the physical and chemical properties of soils do not suggest a substantial contribution from grassland burning to soil fertility in our study area. Optimal soil fertility conditions typically support healthy plant growth and development, leading to greater productivity [77]. On the other hand, 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 [23,78]. Indeed, our findings one-year post-fire suggest that wildfires stimulated the growth of other herbaceous species in Cusco. This is consistent with the perspectives of individuals interviewed across the study areas, who anticipate varying responses from the grasslands, both in terms of quantity and quality, in the coming months due to burning practices [14,15]. Our findings also indicate vegetation recovery of up to 78% (or less), approximately three years after the wildfire. This aligns closely with the grassland recovery timeframe (1-4 years) reported by the population during the interviews.

The multifaceted nature of wildfires, which encompasses social, economic, and political factors, often complicates stakeholder efforts to reach a common understanding on how to address the problem and propose adequate solutions [79]. Current international governmental strategies are oriented towards adopting prevention measures and establishing control plans that include initiatives for impact mitigation training, prescribed burns, alternative methods for the disposal of agricultural waste, and imposing penalties for unauthorized burning [80]. However, in Peru, existing measures are predominantly punitive, encompassing both imprisonment and significant monetary fines [81,82], 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 firefighting training. Implementing policies in Peru that incorporate the use of fire by farming communities presents a significant challenge for decision-makers [42,83]. Furthermore, there exists a wide range of sectoral, disciplinary, and personal perspectives among those involved in the different stages of wildfire management, which have yet to find a coordinated space for joint action. Therefore, research is needed in Peru to understand how people use fire (controlled burns or prescribed fire) and what role the involved institutions should play [79].

On the other hand, the increasing frequencies of dry days or hot days in Peru are linked to the escalating impacts of wildfires on grassland ecosystems [13,41], creating conditions that have led to a rise in the frequency of wildfire emergencies and loss of human life. Indeed, extreme events such as droughts are associated with an approximate increase of up to 400% in wildfire frequency over the last two decades [42]. By the end of this century, the Intergovernmental Panel on Climate Change (IPCC) has projected that temperatures in tropical regions could potentially increase by up to 4.8 °C [84]. This underscores the importance of implementing appropriate measures and strategies in the management of fire use, known as corrective management, instead of solely prioritizing the management of wildfires, which involves both prospective and reactive approaches, by the government authorities of 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, southern Peru. Two wildfires that occurred in grasslands during 2022 in two farmer communities of Cusco-Peru were studied. Andean grassland ecosystems are fragile environments facing significant threats, necessitating better management strategies. The results indicate that soil property values initially increased after the fire, between the second and third seasons of analysis (the beginning of the rainy season and the rainy season), and 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. Moreover, our findings suggest that modifications in soil properties are driven by the soil temperature during burning because the fuel load from grass is very low, contributing to the stimulation of regeneration of other herbaceous species after the rainy season. It is estimated that the load of vegetative fuel from the Andean grasslands after burning will be fully recovered between 4 and 6 years, a timeframe also described by the local population.

Given the burning practices carried out by the population and their interests, research on the comparison of burn severities by controlled burns on grasslands needs to be conducted. 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 assist decision-makers in formulating policies, regulations, and proposals for reducing wildfire impacts, as well as restoring vegetation in the Andean region of Cusco.

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