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Effects of Low-Intensity Prescribed Burning with Minimal Soil Heating on Soil Properties and Mycorrhizal Infectivity in an Inter-Andean Montane Shrubland of Southern Ecuador

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Abstract

Fire is a recurrent ecological process in Andean ecosystems, yet its effects on soil properties and arbuscular mycorrhizal fungal (AMF) infectivity under low-intensity conditions remain poorly understood. The study was conducted with limited spatial replication ($n = 3$ plots per treatment) in an inter-Andean montane shrubland of southern Ecuador, with nine plots assigned to upslope burning, downslope burning, or an unburned control. Fire behavior, soil physicochemical properties, and AMF infectivity using the MSI_{50} bioassay were assessed. Maximum soil temperatures at 5 cm depth reached only29.2 to 35.8 °C in burned plots, compared to a baseline of 20.8 °C in unburned controls, confirming minimal soil heating. No, statistically detectable changes in soil chemical properties were observed, although the limited statistical power precludes ruling out ecologically meaningful variations. Upslope fires spread faster and had shorter heat residence times than downslope fires, though these differences were not statistically significant ($p = 0.10$). Median MSI_{50} values were 9.74%, 9.75%, and 18.08% under downslope burning, upslope burning, and the unburned control, respectively, with no significant treatment effect ($p = 0.668$). The downslope-burning treatment included one exceptionally high value (82.42%) visible as an outlier. Multivariate ordinations and correlation analyses are presented strictly as exploratory due to the small sample size and did not reveal statistically supported associations between fire behavior variables and mycorrhizal infectivity. Overall, low-intensity burning with minimal soil heating produced limited short-term changes in soil properties and no detectable decline in AMF infective potential, suggesting the functional AMF propagule bank remains resilient under these conditions.

Keywords: arbuscular mycorrhizal fungi; soil mycorrhizal infectivity; MSI_{50}; low-intensity fire; prescribed burning; fire spread direction; inter-Andean montane shrubland

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1. Introduction

Fire is a fundamental ecological process that shapes the structure, composition, and functioning of terrestrial ecosystems worldwide. In addition to altering vegetation and biogeochemical cycles, fire directly affects the physical, chemical, and biological properties of soils, thereby influencing post-fire recovery processes and overall ecosystem resilience [1,2]. However, the magnitude and direction of these effects largely depend on fire severity, heating duration, fuel characteristics, and local environmental conditions [3,4]. While fire severity reflects the overall ecological impact, the initial subterranean heat transfer is directly driven by fire intensity, which determines the thermal energy released during combustion and conducted into the soil [3].

The effects of fire on soils have been extensively documented in temperate, Mediterranean, and Andean ecosystems, where moderate and high-severity fires commonly induce significant changes in soil pH, nutrient availability, organic matter, and hydrophysical properties [1,5,6]. In contrast, low-severity fires generally cause only limited alterations because heat transfer to the upper soil horizons is relatively low [2]. Nevertheless, even relatively small thermal disturbances may affect sensitive biological processes, particularly those associated with the soil microbiota [7].

Among the most important soil microorganisms supporting terrestrial ecosystem functioning are arbuscular mycorrhizal fungi (AMF), which form symbiotic associations with most terrestrial plant species and contribute to plant nutrient acquisition, stress tolerance, and ecosystem functioning [8]. These symbioses are also critical for plant establishment and recovery following disturbance, as inoculation with native AMF can enhance the growth of tropical tree seedlings used in restoration [9]. In southern Ecuador, diverse AMF communities have been documented across tropical montane forests and reforestation sites, where the persistence of suitable fungal symbionts may contribute to vegetation regeneration [10]. AMF communities have also been documented across a broad elevational gradient from 1000 to 4000 m a.s.l., spanning premontane and montane forests to high-elevation páramo, with community composition changing significantly with elevation [11]. Moreover, in high-Andean wetlands above 3000 m a.s.l., mycorrhizal colonization persisted across sites with contrasting degrees of disturbance and showed less variation than fine-root biomass [12]. Despite their occurrence across these contrasting Andean environments, AMF remain potentially vulnerable to fire because their propagules and extraradical mycelium are exposed to soil heating, particularly in the upper soil layers where thermal effects are greatest [13].

Responses of AMF to fire are highly variable and may depend on fire severity, ecosystem characteristics, and time since disturbance. AMF community composition, diversity, and phylogenetic structure can be significantly altered during the early post-fire period, although communities may recover over longer timescales [14]. In the Brazilian Cerrado, fire initially affected AMF community parameters, whereas spore density and root colonization subsequently reached values comparable to those in unburned areas [15]. One year after wildfire, AMF responses have also been shown to vary among community attributes, with increased spore abundance and root colonization but reduced species diversity in burned areas [16]. Responses of infective AMF propagules have also been examined under forest restoration treatments involving prescribed burning, with greater densities of infective propagules reported in treated than in untreated plots [17]. Together, these findings highlight the importance of evaluating not only AMF abundance, diversity, and root colonization, but also the capacity of soil inoculum to establish new mycorrhizal associations after fire. However, the response of soil mycorrhizal infectivity to low-severity fire remains poorly understood, particularly in tropical Andean ecosystems.

In this context, inter-Andean montane ecosystems of southern Ecuador provide a relevant setting for examining belowground responses to fire. Recent studies in the region

have shown that both soil responses and fire behavior vary substantially with fire severity and local environmental conditions, including topography, fuel characteristics, and elevation [5,18,19]. However, much less is known about the response of belowground biological components, particularly AMF infective potential. Addressing this gap is important for understanding whether low-severity fire can alter soil processes involved in the establishment of plant–fungal symbioses in these ecosystems.

The present study evaluated the effects of experimental low-severity burns on soil physicochemical properties and AMF infectivity in an inter-Andean montane shrubland in the Loja Basin, southern Ecuador. Specifically, we assessed (i) changes in soil physicochemical properties, (ii) the response of mycorrhizal infectivity, and (iii) the relationships between mycorrhizal infectivity, fire-behavior variables, and post-fire soil conditions. We hypothesized that low-severity prescribed burning would not significantly reduce the soil mycorrhizal infective potential due to minimal heat transfer into the mineral soil. We further explored whether variation in mycorrhizal infectivity was associated with differences in fire behavior and post-fire soil conditions.

2. Materials and Methods

2.1. Study Area and Experimental Design

The study was conducted in the southern Ecuadorian Andes, in the Punzara sector, Loja Canton, Loja Province, at an elevation of 2263 m a.s.l. (UTM: 698,339 m E, 9,553,149 m S; Zone 17M) (Figure 1). The study site is located within an inter-Andean montane shrubland characterized by a matrix of secondary vegetation associated with historical anthropogenic disturbance. The plant community in the experimental plots is dominated by five species that collectively represent the characteristic vegetation of inter-Andean montane shrublands [20]. The most abundant species is *Tibouchina laxa* (*Melastomataceae*, 79.56% relative abundance across plots), which forms ericoid mycorrhizal associations adapted to acidic, high-altitude soils. The second most dominant species is *Bidens triplinervia* (*Asteraceae*, 65.40%), followed by *Cuphea racemosa* (*Lythraceae*, 38.85%), Desmodium tortuosum (*Fabaceae*, 23.26%), and *Daucus montanus* (*Apiaceae*, 21.47%). Notably, four of these five dominant species (*B. triplinervia*, *C. racemosa*, *D. tortuosum*, and *D. montanus*) are known hosts of arbuscular mycorrhizal fungi (AMF), while *T. laxa* forms ericoid mycorrhizas. The presence of *Desmodium tortuosum*, a nitrogen-fixing legume that also forms AMF associations, is particularly relevant as it contributes both to soil fertility and to the AMF spore bank. In the Loja canton, these ecosystems are embedded in a rural landscape subject to significant human influence, where small-scale agriculture and livestock raising are the predominant land uses and play an important role in the livelihoods of rural communities [21].

The climate is classified as temperate-equatorial subhumid, with a mean annual precipitation of 1123.8 mm and a mean annual temperature of 16.4 °C. Precipitation shows marked interannual variability, ranging from 752.7 to 1848.1 mm annually based on records from the La Argelia M0033 meteorological station for the 2004–2013 period. Rainfall follows a pronounced seasonal pattern, with a wetter period from October to April and a relatively dry period from May to September [22]. During the dry season, reduced fuel moisture may favor fire occurrence, while local variation in vegetation moisture, fuel characteristics, and topography can influence fire behavior in Andean shrublands of southern Ecuador [5,18]. The study area has a complex and rugged topography, characterized by abrupt transitions between valleys and mountain ranges [22]. Soils in the study area have been classified as Dystrudepts and Hapludolls, including the Andic Dystrudepts and Andic Hapludolls subgroups, following the USDA Soil Taxonomy system [22,23]. Previous studies [22] also described these soils as sandy loam and strongly acidic, with pH values ranging from 4.8 to 5.8.

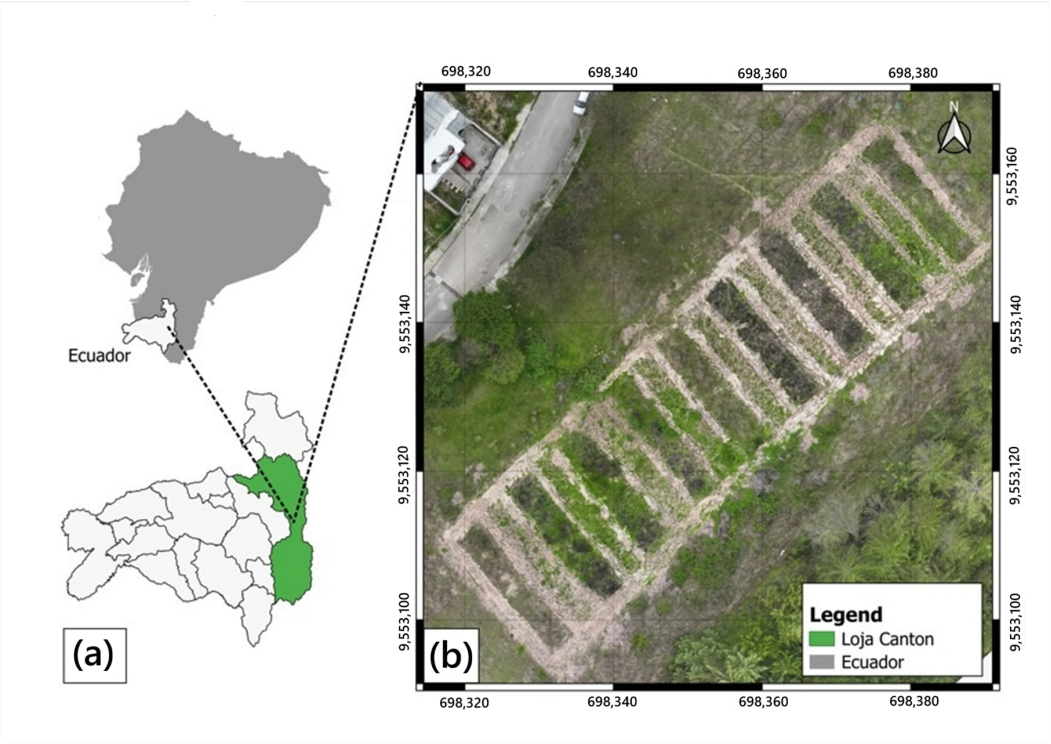


Figure 1. Location of the study area. (**a**) Map of Ecuador showing the location of Loja Province and Loja Canton (green). (**b**) High-resolution aerial image of the experimental site in Loja Canton, showing the arrangement of the rectangular experimental plots. The coordinate system is Universal Transverse Mercator (UTM). The north arrow is shown in the upper-right corner.

The experimental prescribed burns were conducted with the official authorization of the Ministerio del Ambiente, Agua y Transición Ecológica (MAATE) of Ecuador, under permit number MAATE-DA-2024-8189-E.

2.2. Burning Experiment Design

The experimental site was located on the outskirts of Loja City, in the Punzara sector of southern Ecuador, on slopes ranging from 14 to 21°. The site was enclosed by a fence consisting of wooden posts and barbed wire, which excluded livestock (Bos taurus) and minimized grazing and trampling disturbance. Although the area had experienced previous anthropogenic disturbance, long-term livestock exclusion had allowed the shrubland vegetation to develop with limited recent physical disturbance. The site also had one of the longest documented fire-free periods within the study area, resulting in substantial accumulation of fine fuels before the experimental burns [19].

Nine experimental plots were established on northwest-facing slopes following a randomized complete block design (RCBD) with three blocks and three plots per block (Figures 1b and 2). Each block contained one unburned control, one upslope-burn plot, and one downslope-burn plot, with treatments randomly assigned within blocks. Thus, each treatment was replicated three times. Each plot measured 4 × 20 m (80 m^2), and adjacent plots were separated by 5-m-wide firebreaks to minimize lateral fire spread between experimental units. No additional fuel was added to the burn plots; experimental fires were conducted using only the naturally accumulated fuel present within each plot, following the approach of previous experimental burning studies [24].

Two fire-propagation treatments were applied. In the upslope treatment, fire was ignited at the lower end of the plot and allowed to propagate uphill, whereas in the downslope treatment, fire was ignited at the upper end and allowed to propagate downhill. In both

treatments, fire was initiated using the strip-head firing technique [25]. For the upslope treatment, the ignition line (Ig) was established 0.30 m inside the lower plot boundary, whereas for the downslope treatment it was established along the upper plot boundary, thereby maintaining the intended direction of fire propagation while reducing the risk of fire escaping the experimental plots (Figure 2). Fires were ignited using a 5-L drip torch filled with a diesel–gasoline mixture (75:25, v/v).

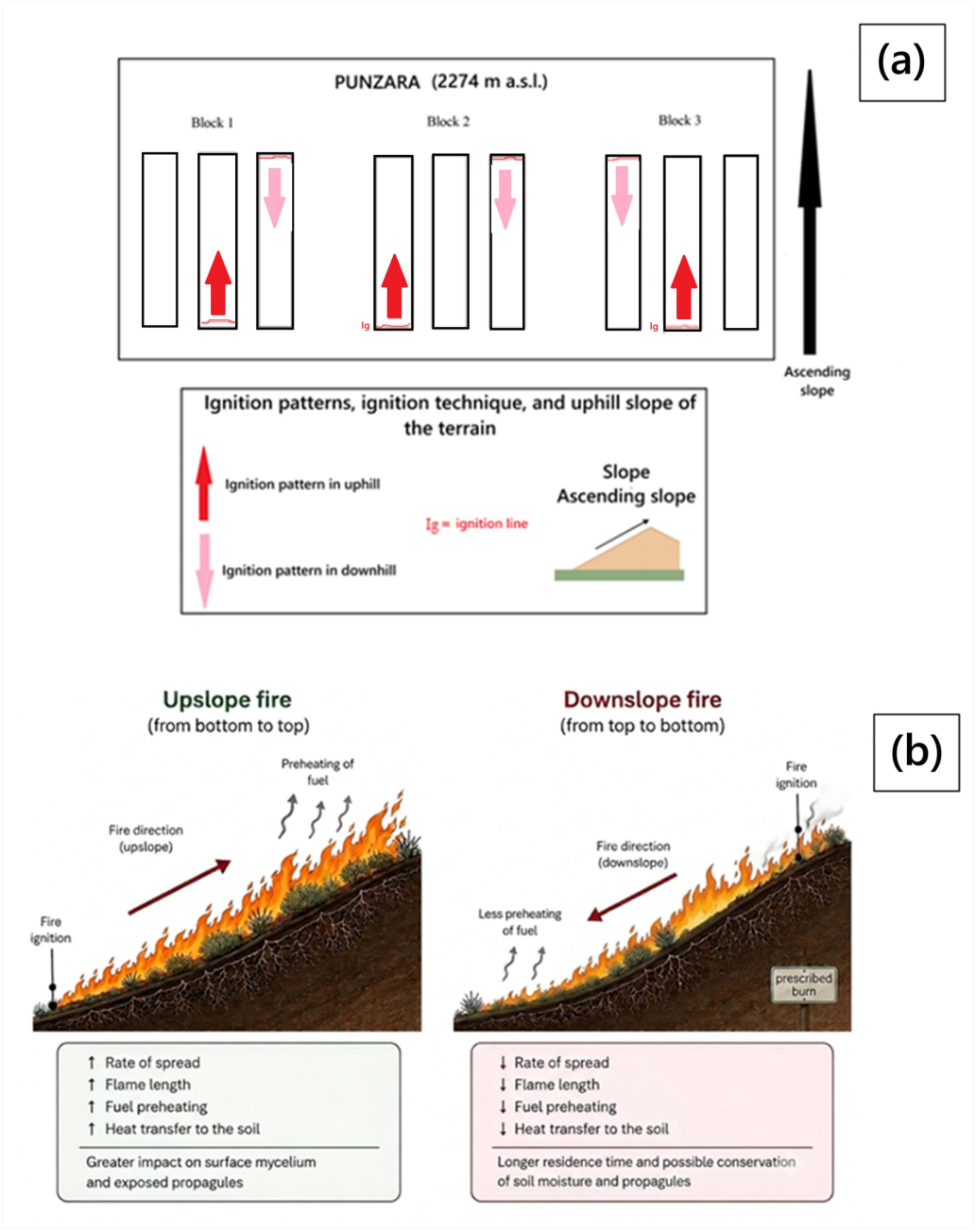


Figure 2. Experimental burning design. (**a**) Spatial arrangement of the three randomized complete blocks, each containing one unburned control, one upslope-burn plot, and one downslope-burn plot. Red arrows indicate upslope fire propagation (from bottom to top), whereas pink arrows indicate downslope fire propagation (from top to bottom). (**b**) Schematic representation of the two fire-propagation directions.

In situ meteorological conditions were monitored following the protocol described by [18]. During each burn, air temperature, relative humidity, wind speed, and wind direction were recorded using a Kestrel 5500 portable weather meter (Kestrel Instruments,

Boothwyn, PA, USA), while incoming solar radiation was measured with an Apogee SP-110 pyranometer (Apogee Instruments, Logan, UT, USA). Experimental burns were conducted between 09:00 and 15:00 h in October–November 2024, during the period of the day characterized by relatively high air temperature and solar radiation and lower relative humidity at the study site [26].

2.3. Determination of Fire Behavior and Soil Heating

To assess the thermal effects of experimental burning on soil physicochemical properties and arbuscular mycorrhizal fungal (AMF) infectivity, maximum soil temperature (T_{max}) was used as an indicator of the magnitude of soil heating during burning [4]. Soil heating is particularly relevant for AMF because their infective propagules, including spores, hyphae, and colonized root fragments, may be affected by elevated temperatures, with thermal effects depending on the magnitude and depth of soil heating [13].

Soil temperature was continuously recorded during the experimental burns at a depth of 5 cm using three Type-K thermocouples installed along the central longitudinal axis of each plot and connected to EasyLog EL-USB-TC data loggers [19]. For each plot, the maximum temperature recorded by each thermocouple during passage of the fire front was identified, and the three values were averaged to obtain a plot-level estimate of T_{max} at 5 cm depth. This approach was used to characterize the thermal exposure of the shallow soil layer while accounting for spatial variability in temperature within each experimental plot.

For the purposes of this study, soil thermal conditions at 5 cm depth were interpreted using operational temperature ranges of <60 °C, 60–200 °C, and >200 °C. These ranges were used as an interpretative framework rather than as a general classification of fire intensity. Temperatures around 50–60 °C may adversely affect heat-sensitive soil organisms, including fungi [3,4,7]. Soil heating below 200 °C primarily affects biological properties, whereas temperatures above 200 °C increasingly affect chemical and physical soil properties [14,27]. Certini [1] further emphasized that the magnitude of fire effects on soil depends on both the temperature reached and the duration of heating. Accordingly, thermal conditions in the present study were characterized using maximum soil temperature (T_{max}) recorded at 5 cm depth rather than flame or surface temperature.

In addition to T_{max}, fire rate of spread (R) and soil-heating residence time were quantified to characterize fire behavior and the duration of thermal exposure. The rate of spread (R, m s^{-1}) was calculated as the linear distance traveled by the fire front divided by the elapsed time between two consecutive measurement stations:

$$\mathrm{ROS} = d/t$$

where d is the distance between consecutive stations (m) and t is the elapsed time (min) between the arrival of the fire front at those stations. Within each 4 × 20 m plot, four consecutive 5-m segments (0–5, 5–10, 10–15, and 15–20 m) were established along the central measurement axis. Four metal rods, together with the plot boundaries, served as reference stations for recording the arrival time of the fire front. This procedure yielded segment-level estimates of fire rate of spread, which were subsequently averaged to obtain a plot-level estimate [19].

Residence time was defined as the duration for which soil temperature at 5 cm depth remained within the predefined thermal range of 28–40 °C. The lower threshold (28 °C) corresponded to the mean temperature recorded in the unburned control plots at the corresponding time of experimental burning, whereas 40 °C was established as the upper threshold based on the maximum temperature observed during the experimental burns. For each thermocouple, residence time was calculated from the temperature time series as the cumulative duration within this thermal range, and the resulting values were averaged

across the three thermocouples to obtain a plot-level estimate of soil-heating residence time. This metric complemented T_{max} by accounting for the duration of thermal exposure. However, it is important to clarify that this specific 28–40 °C thermal band was selected strictly as a descriptive index of the flame front's passage duration over the soil surface, rather than as a measure of lethal thermal dose, as these temperatures are well below the threshold required to adversely affect soil microorganisms or AMF propagules [4,13].

2.4. Soil and AMF Sampling

Soil sampling for physicochemical analyses was conducted 24 h after the experimental burns to characterize the short-term changes in soil properties following fire exposure. Before sampling, the surface ash layer, which had a mean thickness of approximately 3 cm, was carefully removed following the protocol described by [19]. The soil–ash interface was then gently scraped with a metal spatula to remove charred residues and superficial pyrogenic materials, thereby minimizing the incorporation of particulate charcoal and other surface-derived materials into the soil samples.

For soil chemical analyses, nine subsamples were systematically collected from the upper soil horizon (0–10 cm) within each experimental plot using a standardized metal sampling cylinder (283 cm^3; 6 cm diameter × 10 cm height). The nine subsamples from each plot were homogenized in the field to obtain one representative composite sample per plot. Thus, the experimental unit for subsequent chemical analyses was the plot, resulting in nine composite samples corresponding to the three treatments and three replicate plots per treatment. To minimize variability associated with the sampling procedure, all samples were collected by the same operator using the same sampling device [5].

For the determination of soil physical properties, three undisturbed soil cores were collected from each plot at the same depth (0–10 cm) after removal of the surface ash layer. A total of 27 undisturbed cores (9 plots × 3 cores per plot) were collected for determination of bulk density, total porosity, and gravimetric soil moisture content. The cores were placed in pre-labeled plastic bags and transported to the laboratory for subsequent processing.

AMF infectivity was assessed three months after the experimental burns, rather than immediately after fire, because short-term post-fire conditions may not fully reflect the persistence or subsequent response of soil infective propagules [28]. Four soil cores were collected systematically from the upper soil horizon (0–10 cm) within each experimental plot and homogenized to obtain one composite sample per plot. This resulted in nine composite soil samples, corresponding to the three treatments and three replicate plots per treatment, which were subsequently used for the soil mycorrhizal infectivity assay described in Section 2.5. Nine subsamples were collected for physicochemical analysis to capture the high spatial heterogeneity of soil properties, while four cores were deemed sufficient for AMF analysis, as mycorrhizal colonization is assessed via a standardized, highly sensitive bioassay that integrates the infective potential of the composite sample.

2.5. Soil Mycorrhizal Infectivity Assay (MSI_{50})

Soil mycorrhizal infectivity was evaluated using the soil dilution bioassay described by [29]. Fresh composite soil samples from each experimental plot were transported to the laboratory and air-dried within 24 h of collection to reduce their high moisture content and allow adequate homogenization before preparation of the dilution series. Samples were not sieved. During the following week, the homogenized soil samples were mixed with sterilized sand to obtain five concentrations of natural soil (1, 3, 10, 30, and 100% v/v) The sand used as a diluent was sterilized twice by autoclaving at 121 °C for 1 h, with a 24-h interval between autoclaving cycles, following the procedure described by [30]. Maize (*Zea mays* L.) was grown in 50-mL containers for six weeks under an 8-h light/16-h dark photoperiod.

Plants were watered twice weekly with tap water to field capacity, and no nutrient solution or fertilizer was applied. Four plants were established independently at each dilution level, with each plant constituting one bioassay experimental unit, resulting in a total of 180 bioassay experimental units (9 composite samples × 5 natural soil concentrations × 4 replicates). No separate sterile control was included. Each of the 4 replicates per concentration consisted of one individual plant grown in a single pot. Within the Firth logistic regression modeling, these four plants per concentration per plot were treated as subsamples to estimate the plot-level MSI_{50} and its uncertainty.

After the bioassay period, roots were harvested, cleared in 20% KOH for 30 min at 90 °C, rinsed three times with water, acidified in 10% HCl for 15 min at room temperature, and stained with trypan blue for 15 min at 90 °C following [31]. Stained roots were initially screened under a stereomicroscope at 50× magnification for evidence of fungal colonization. Root sections showing apparent colonization were subsequently mounted on microscope slides and examined under a compound microscope at 100×–400× magnification to confirm the presence of arbuscular mycorrhizal fungal (AMF) structures and distinguish them from structures of other root-associated endophytic fungi. Colonization was confirmed based on the presence of characteristic AMF structures, including arbuscules, hyphal coils, vesicles, and aseptate hyphae, and was recorded as a binary response (colonized = 1, non-colonized = 0). The percentage of colonized plants was calculated by dividing the number of colonized plants by the total number of plants assessed at each soil dilution. Representative micrographs of the AMF structures used to confirm colonization are provided in Figure S1.

Soil mycorrhizal infectivity was expressed as the Mycorrhizal Soil Infectivity 50 (MSI_{50}), defined as the proportion of natural soil required to achieve colonization in 50% of host plants. MSI_{50} values were estimated independently for each experimental plot from the relationship between the percentage of colonized plants and the logarithm of soil concentration, following [29]. Plot-specific MSI_{50} values were subsequently used to compare soil mycorrhizal infectivity among treatments and to evaluate its relationships with soil physicochemical properties and fire behavior variables. MSI_{50} provides an integrated functional measure of the infective potential of the processed field soil; it does not quantify AMF spore abundance or distinguish among the types of infective propagules responsible for colonization. Lower MSI_{50} values indicate greater soil mycorrhizal infectivity.

2.6. Soil Analyses

In the laboratory, soil physical properties were determined first. Bulk density was determined using the undisturbed core method. Samples of known volume were oven-dried at 105 °C for 24 h or until constant mass, and bulk density was calculated from the oven-dry soil mass and core volume [32]. Gravimetric soil moisture content was determined from the mass loss upon oven-drying and calculated as the difference between field-moist and oven-dry sample masses relative to the oven-dry mass [32]. Total porosity was calculated from bulk density and particle density, assuming a particle density of 2.65 g cm^{-3} [32].

For soil chemical analyses, soil pH was measured potentiometrically in a soil-to-distilled-water suspension (1:2.5, w/v) using a hydrogen-ion-selective electrode (Thermo Scientific Orion, Waltham, MA, USA). Soil organic matter (SOM) was determined by wet oxidation using the Walkley–Black method [33]. Total nitrogen was determined by Kjeldahl digestion and distillation following AOAC Official Method 2001.11 using a VELP Scientifica system (VELP Scientifica, Usmate, Italy). Available phosphorus was determined by UV–Vis spectrophotometry using a Thermo Scientific Genesys 10S spectrophotometer (Thermo Fisher Scientific, Waltham, MA, USA) after extraction with the Bray I method [34]. Exchangeable potassium was determined by atomic absorption spectrophotometry using a PerkinElmer AAnalyst 400 instrument (PerkinElmer, Waltham, MA, USA).

2.7. Statistical Analyses

The data were organized in spreadsheets and tested for normality using the Shapiro–Wilk test and for homogeneity of variances using Levene's test to determine the suitability of parametric or non-parametric statistical methods. All statistical analyses were performed at a significance level of $\alpha = 0.05$.

To evaluate the effects of burning treatments (control, upslope burning, and downslope burning) on soil chemical and physical properties, as well as on the maximum temperature recorded at a depth of 5 cm, a one-way analysis of variance (ANOVA) was performed, followed by Tukey's honestly significant difference (HSD) post hoc test ($\alpha = 0.05$) to identify pairwise differences among treatments. Results were expressed as mean ± standard deviation.

For the mycorrhizal soil infectivity index (MSI_{50}), values were calculated independently for each experimental plot and used as the experimental units for statistical comparisons among treatments ($n = 3$ plots per treatment). Although MSI_{50} values met the assumption of normality (Shapiro–Wilk, $p > 0.05$), differences among treatments were evaluated using the non-parametric Kruskal–Wallis test because of the small sample size and the high within-treatment variability observed in the burned treatments (coefficient of variation > 40%). The H statistic and associated p-value were reported. No effect size was estimated for MSI_{50} because of the limited sample size and the uncertainty associated with the treatment comparison. For variables that did not meet the assumptions of normality or homoscedasticity, specifically heat residence time and fire spread rate, the Kruskal–Wallis test was also applied, and the H statistic and associated p-value were reported.

To evaluate the multivariate patterns and treatment effects on soil properties and mycorrhizal infectivity, a Non-metric Multidimensional Scaling (NMDS) ordination was performed. NMDS was selected over Principal Component Analyses (PCA) because it is a non-parametric technique that does not assume linear relationships or multivariate normality, making it more robust and less prone to overfitting for small sample sizes ($n = 3$ per treatment). Prior to ordination, all continuous variables were standardized (z-scores) to account for differences in measurement units and scales. The NMDS was based on a Bray–Curtis dissimilarity matrix. To statistically test significant differences in the multivariate composition of soil properties among treatments, a Permutational Multivariate Analysis of Variance (PERMANOVA) was conducted using 999 permutations. The goodness-of-fit of the NMDS was evaluated using stress value. Both NMDS and PERMANOVA were performed using the 'vegan' package in R software (ersion 4.6.1). Total porosity was explicitly excluded from all multivariate analyses (NMDS ordinations and correlation matrices) because it is a direct linear transformation of bulk density and carries no independent information; including both variables would introduce perfect collinearity and distort the ordination loadings.

A correlation analysis was performed exclusively on the six plots subjected to experimental burning ($n = 6$), excluding the unburned control plots. This methodological decision was made because fire behavior variables (heat residence time and rate of fire spread) are not defined under non-combustion conditions; therefore, their inclusion would require structurally null values that could generate spurious associations by artificially amplifying the separation between the "absence of fire" and the "fire intensity gradient." Accordingly, the analysis focused on evaluating relationships within the fire intensity gradient, whereas comparisons among treatments were addressed separately. To evaluate the relationships between mycorrhizal infectivity (MSI_{50}), fire behavior variables, and soil physicochemical properties, a Spearman correlation matrix was used.

Following the soil-dilution bioassay framework of Plenchette et al. [29], MSI50 was estimated separately for each experimental plot. Because mycorrhizal colonization was

recorded as a binary response for individual plants, the concentration-response relationship was analyzed using Firth bias-reduced binomial logistic regression [35,36]. For each plot, individual plant colonization status across the five natural-soil concentrations (1, 3, 10, 30, and 100% v/v; four plants per concentration) was modeled as a function of the base-10 logarithm of natural-soil concentration. MSI50 was defined as the natural-soil concentration corresponding to a fitted probability of colonization of 0.5 and was calculated from the fitted intercept and slope of the logistic model. Ninety-five percent confidence intervals for MSI50 were calculated using the delta method on the log10-transformed MSI50 scale, incorporating the variance-covariance matrix of the fitted coefficients, and subsequently back-transformed to the original concentration scale. Firth logistic models were fitted in R version 4.6.1 using the logistf package version 1.26.1.

Plot-level MSI50 estimates were subsequently compared among treatments using the Kruskal–Wallis rank-sum test, with the experimental plot as the independent unit ($n = 3$ plots per treatment). Given the limited number of independent experimental units, an additional sensitivity analysis was conducted to characterize the ability of the experimental design to detect treatment effects. For three treatment groups, a significance level of 0.05, and 80% power, the minimum detectable standardized effect was approximated using a noncentral F distribution. This calculation was used only to characterize the sensitivity of the experimental design and was not used for testing treatment differences or as a post hoc estimate of observed statistical power.

3. Results

3.1. Effect of Fire on the Chemical Properties of the Soil

The analyses of soil chemical properties revealed similar patterns among the burn treatments and the unburned control (Table 1). Soil organic matter (SOM) concentrations did not differ significantly among treatments, ranging from 1.7% in the downslope-burning plots to 3.1% in the unburned control ($p = 0.308$). These results indicate that the experimental burns did not cause a statistically significant reduction in SOM in the surface soil layer.

Table 1. Effect of fire on soil chemical properties in experimental burns in southern Ecuador. Different letters indicate statistically significant differences among treatments (Tukey's HSD, $\alpha = 0.05$).

Treatment	SOM (%)	pH	N (%)	P (mg/kg)	K (cmol/kg)
Unburned control	3.1 ± 1.6 [a]	4.8 ± 0.2 [a]	0.2 ± 0.1 [a]	12.5 ± 9.9 [a]	0.4 ± 0.1 [a]
Upslope burning	2.9 ± 0.17 [a]	4.9 ± 0.2 [a]	0.1 ± 0.0 [a]	19.7 ± 1.5 [a]	0.6 ± 0.1 [a]
Downslope burning	1.7 ± 1.03 [a]	4.8 ± 0.1 [a]	0.1 ± 0.1 [a]	12.1 ± 7.0 [a]	0.5 ± 0.1 [a]
p-value	0.308	0.768	0.284	0.394	0.377

Soil pH remained slightly acidic across all treatments, with no significant differences among treatments ($p = 0.768$). The increase in soil pH commonly reported following higher-intensity fires was not observed under the experimental burning conditions. Similarly, total nitrogen ($p = 0.284$), available phosphorus ($p = 0.394$), and exchangeable potassium ($p = 0.377$) showed no significant differences among treatments. Overall, the experimental burns did not significantly alter the measured chemical properties of the surface soil.

3.2. Effect of Fire on the Physical Properties of the Soil

Regarding soil physical properties, significant differences among treatments were observed for porosity and bulk density (Table 2). Porosity (Pr) was significantly higher in the upslope-burning treatment (76.4 ± 1.8%) than in both the unburned control (69.7 ± 1.9%) and the downslope-burning treatment (69.6 ± 2.0%; $p = 0.007$). Soil moisture did not differ significantly among treatments ($p = 0.386$), whereas bulk density was significantly lower in the upslope-burning treatment (0.6 ± 0.0 g cm^{-3}) than in both the unburned control (0.8 ± 0.0 g cm^{-3}) and the downslope-burning treatment (0.8 ± 0.1 g cm^{-3}; $p = 0.007$). Overall, these results indicate that the main changes in soil physical properties following the experimental burns occurred under upslope burning, which was characterized by higher porosity and lower bulk density.

Table 2. Effect of fire on soil physical properties in experimental burns in southern Ecuador. Different letters indicate statistically significant differences (Tukey's HSD: 0.05).

Treatment	Porosity (%)	Soil Moisture (%)	Bulk Density (g cm^{-3})
Unburned control	69.7 ± 1.9 ^{a}	11.9 ± 3.3 ^{a}	0.8 ± 0.0 ^{a}
Upslope burning	76.4 ± 1.8 ^{b}	13.0 ± 4.4 ^{a}	0.6 ± 0.0 ^{b}
Downslope burning	69.6 ± 2.0 ^{a}	7.5 ± 6.4 ^{a}	0.8 ± 0.1 ^{a}
p-value	0.007	0.386	0.007

3.3. Heat Transfer to the Ground and Fire Behavior

The maximum soil temperature at 5 cm depth reached means of 35.8 ± 3.5 °C in upslope burning and 29.2 ± 4.2 °C in downslope burning, compared to a baseline of 20.8 ± 0.3 °C in unburned controls. Statistical comparison of the burned plots only revealed no significant differences in maximum soil temperature between fire directions (exact Kruskal–Wallis, $p = 0.127$). Regarding fire behavior parameters, which were analyzed exclusively for the burned treatments, heat residence time at 5 cm soil depth differed marginally between burning methods (exact Kruskal–Wallis, $p = 0.046$) (Table 3).

Table 3. Fire behavior variables and maximum soil temperature (T_{max}) at 5 cm depth across treatments. Values represent standard deviation ($n = 3$ independent plots per treatment). Different letters indicate statistically significant differences between treatments based on exact Kruskal–Wallis tests ($\alpha = 0.05$).

Treatments	Maximum Soil Temperature (T_{max}) at 5 cm Depth (°C)	Heat Residence Time at 5 cm Soil Depth (s)	Rate of Fire Spread (ROS; m min^{-1})
Unburned control	20.8 ± 0.3	——–	——–
Upslope burning	35.8 ± 3.5 ^{a}	49.2 ± 24.5 ^{a}	1.0 ± 0.2 ^{a}
Downslope burning	29.2 ± 4.2 ^{a}	120.8 ± 0.4 ^{b}	0.8 ± 0.2 ^{a}
p-value	0.1266	0.0463	0.3758

Note: The unburned control T_{max} represents ambient baseline temperature and was excluded from statistical comparisons with burned treatments, as comparing ambient conditions with peak fire-front temperatures violates the homogeneity of variance assumption and represents fundamentally different ecological quantities. Heat residence time showed marginal significance ($p = 0.046$), interpreted cautiously given the small sample size.

Downslope burns recorded a heat residence time of 120.7 ± 0.4 s, which was longer than that observed in upslope burns (49.2 ± 24.5 s). The rate of fire spread (ROS) did not differ significantly between burning methods (exact Kruskal–Wallis, $p = 0.376$), with values of 1.0 ± 0.2 m min^{-1} in downslope burns and 0.8 ± 0.2 m min^{-1} in downslope burns (Table 3). These results reveal an inverse pattern between the fire behavior variables: upslope burns spread more rapidly but exhibited a shorter heat residence time in the soil,

whereas downslope burns advanced more slowly but maintained heat in contact with the soil profile for a longer period.

3.4. Effect of Fire on Mycorrhizal Infectivity of Soil (MSI_{50})

Plot-level MSI_{50} estimates, derived from Firth bias-reduced binomial logistic models, ranged from 6.98% to 82.42% (Table S1). Eight of the nine plots showed a statistically detectable positive concentration-colonization relationship (penalized likelihood-ratio $p < 0.05$). The remaining plot (P7, downslope burning) showed a weaker concentration response and substantial uncertainty in its MSI_{50} estimate (82.42%, 95% CI = 6.29–1080.02%).

Median MSI_{50} values were 18.08% in the control, 9.75% under upslope burning, and 9.74% under downslope burning (Figure 3). Despite these numerical differences, no statistically detectable differences in MSI_{50} were found among treatments (Kruskal–Wallis, H = 0.807, df = 2, $p = 0.668$). The effect-size sensitivity analysis indicated that, with three independent plots per treatment, the minimum standardized effect detectable with 80% power at a significance level of 0.05 was approximately Cohen's f = 1.36, indicating limited sensitivity to smaller treatment effects. Overall, the results show that the low-intensity experimental burns did not produce a statistically detectable reduction in soil mycorrhizal infectivity, though the high spatial heterogeneity and limited statistical power preclude definitive conclusions regarding the absence of an ecological effect.

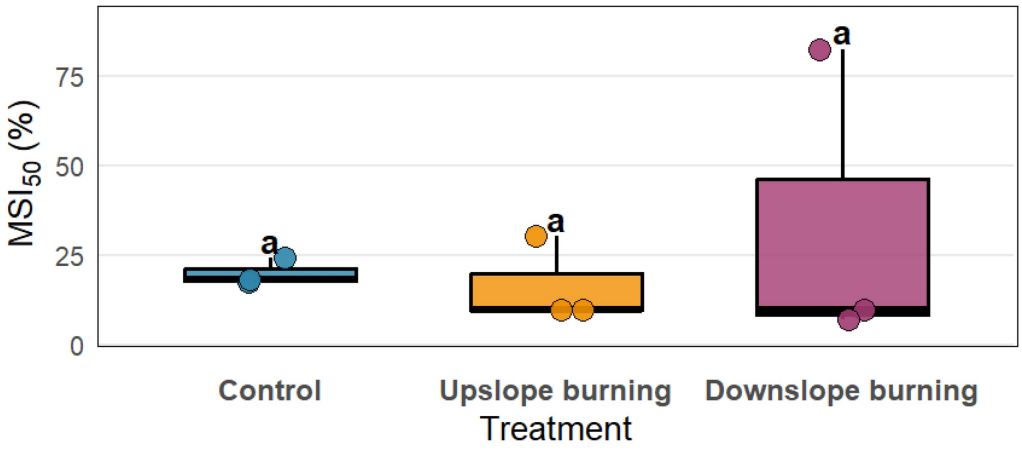


Figure 3. Soil mycorrhizal infectivity assessed using the Mycorrhizal Soil Infectivity 50 (MSI_{50}) index in unburned control, upslope-burning, and downslope-burning treatments. MSI_{50} values were estimated for each plot using Firth bias-reduced binomial logistic regression. Lower MSI_{50} values indicate greater soil mycorrhizal infectivity. Boxplots show the median (horizontal line), interquartile range (box), and whiskers extending to 1.5× IQR. Individual plot estimates are shown as circles ($n = 3$ per treatment). The downslope-burning treatment includes one exceptionally high value (82.42%) visible as an outlier. No statistically significant differences were detected among treatments (Kruskal–Wallis, H = 0.807; $p = 0.668$).

3.5. Multivariate Patterns of Soil Properties and Fire Behavior

To comprehensively evaluate the multivariate responses of the ecosystem to burning treatments, two Non-metric Multidimensional Scaling (NMDS) ordinations were performed based on Bray–Curtis dissimilarities of standardized variables. NMDS was selected over Principal Component Analysis (PCA) as it is a non-parametric technique robust to small sample sizes ($n = 3$ per treatment) and does not assume linear relationships, thereby minimizing the risk of overfitting. Total porosity was explicitly excluded from both ordinations because it is a direct linear transformation of bulk density; including both variables would introduce perfect collinearity and distort the ordination loadings.

The first NMDS focused exclusively on soil physicochemical properties and mycorrhizal soil infectivity (MSI_{50}) to isolate the ecological response of the soil to the treatments (Figure 4a). This two-dimensional solution yielded a stress value of 0.08, indicating an excellent representation of the multivariate relationships (stress < 0.1 is considered excellent). The ordination showed partial separation among treatments along the first axis (NMDS1). Unburned control plots (blue) clustered toward the right side of NMDS1, while burned plots dispersed more broadly toward the left and central regions of the ordination space. Notably, upslope-burning plots (orange) exhibited the greatest dispersion along the NMDS2 axis, ranging from negative to positive values, indicating higher within-treatment variability in the multivariate soil response. This dispersion is consistent with the contrasting values of soil moisture, temperature, and MSI_{50} observed among the upslope-burning replicates in the univariate analyses. Downslope-burning plots (purple) occupied intermediate positions along NMDS1, with moderate dispersion.

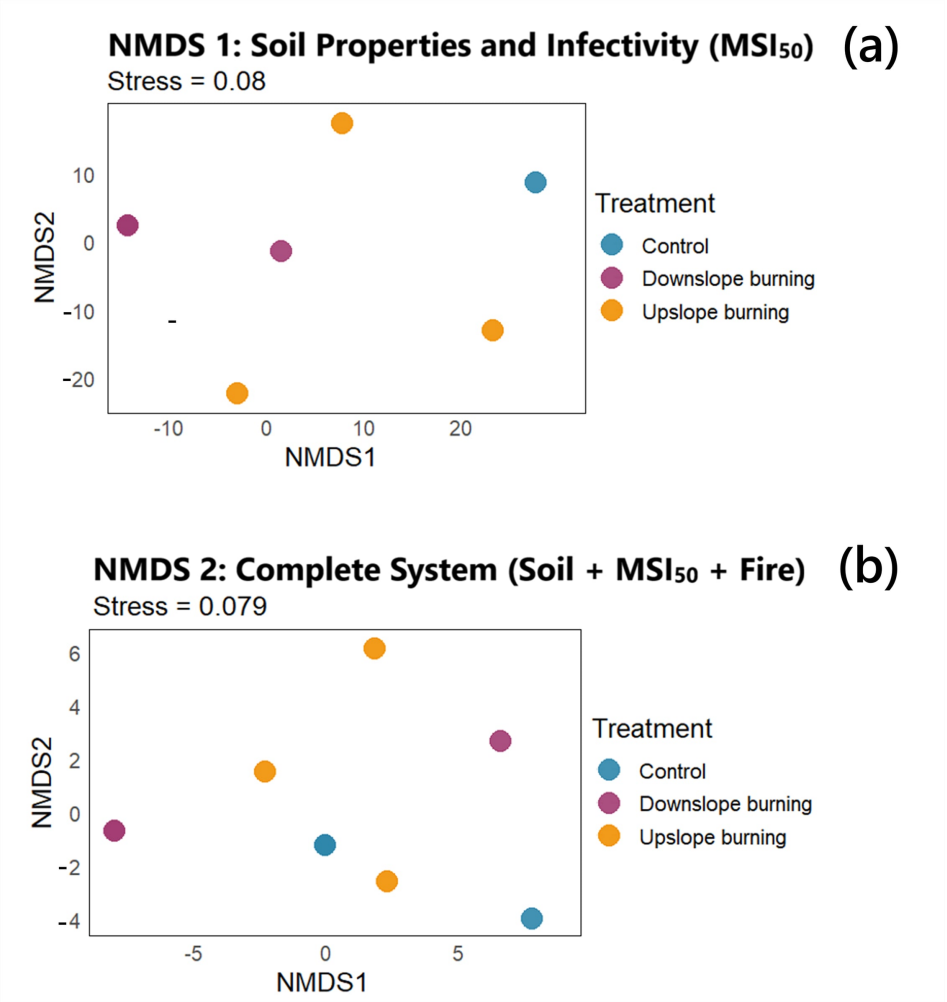


Figure 4. Non-metric Multidimensional Scaling (NMDS) ordinations based on Bray–Curtis dissimilarities of standardized variables across fire treatments in an inter-Andean montane shrubland. (**a**) NMDS1 focused on soil physicochemical properties and mycorrhizal soil infectivity (MSI_0), isolating the ecological response of the soil (stress = 0.118). (**b**) NMDS2 incorporated fire behavior variables (heat residence time and fire spread rate) alongside soil properties and MSI_{50} to visualize the complete soil-fire system (stress = 0.096). Treatments include unburned control, upslope burning, and downslope burning. Both stress values indicate excellent two-dimensional representations of the multivariate data.

The second NMDS incorporated fire behavior variables (heat residence time and fire spread rate) alongside soil properties and MSI_0 to visualize the complete soil-fire

system (Figure 4b). This ordination yielded an even lower stress value of 0.079, indicating an excellent fit. The inclusion of fire behavior variables resulted in a clearer multivariate separation among treatments. Control plots (blue) were positioned toward the lower-right region of the ordination space (reflecting the absence of fire behavior metrics, which are undefined for unburned conditions), while burned plots showed greater dispersion along both axes. Upslope-burning plots (orange) were positioned toward the upper region of the ordination, while downslope-burning plots (purple) occupied intermediate to left positions, reflecting the distinct fire behavior patterns (faster spread and shorter residence time for upslope burns; slower spread and longer residence time for downslope burns).

To statistically test differences in the multivariate composition of soil properties among treatments, a Permutational Multivariate Analysis of Variance (PERMANOVA) was conducted using 999 permutations. The PERMANOVA results showed that the treatment effect explained 98% of the total variation in soil properties ($R^2 = 0.98$); however, this effect was not statistically significant ($F = 147.91$, $p = 0.174$). The lack of statistical significance is consistent with the small sample size ($n = 3$ per treatment) and the high within-treatment variability, particularly in the burned plots. Despite the absence of a significant multivariate treatment effect, the high R^2 value and the clear ordination patterns in both NMDS analyses suggest ecological differentiation among treatments, primarily driven by changes in soil physical properties (bulk density), thermal response (maximum soil temperature at 5 cm depth), and mycorrhizal infectivity (MSI_{50}) following prescribed burning. However, given the limited statistical power, these patterns should be interpreted as exploratory and require validation with greater spatial replication.

3.6. Exploratory Relationships Between Fire Behavior, Soil Properties, and Post-Fire Mycorrhizal Infectivity

Given the small sample size of burned plots ($n = 6$), Spearman correlation analyses between MSI_{50} and fire behavior or soil variables are strictly exploratory and lack statistical power. At $n = 6$, a two-tailed Spearman correlation requires $|r_s| \geq 0.886$ to reach statistical significance at $\alpha = 0.05$; therefore, none of the observed correlations were statistically significant.

Heat residence time showed a very weak negative correlation with MSI_{50} ($r_s = -0.18$, $p = 0.738$), and fire spread rate showed a weak positive correlation ($r_s = 0.25$, $p = 0.633$). Soil moisture showed a very weak positive correlation ($r_s = 0.12$, $p = 0.827$), while maximum soil temperature at 5 cm depth showed a weak positive association ($r_s = 0.23$, $p = 0.658$). Other soil properties showed negligible to weak associations with MSI_{50}: SOM ($r_s = -0.01$, $p = 0.978$), total N ($r_s = -0.01$, $p = 0.978$), available P ($r_s = 0.06$, $p = 0.913$), bulk density ($r_s = -0.06$, $p = 0.913$), and exchangeable K ($r_s = -0.32$, $p = 0.538$). The complete correlation matrix is provided in Supplementary Figure S3, and individual scatter plots of MSI_{50} versus key variables are provided in Supplementary Figure S4 to illustrate the exploratory nature of these relationships.

Given the limited statistical power and the magnitude of the observed coefficients, these correlations should be interpreted as descriptive noise only and do not support causal inferences or predictive relationships.

4. Discussion

4.1. Effect of Low-Intensity Fire on Soil Properties

Our findings indicate that the low-intensity experimental burns did not significantly alter soil chemical properties, including soil organic matter (SOM), pH, total nitrogen, available phosphorus, and exchangeable potassium. This pattern is consistent with previous research conducted in páramo and tropical montane ecosystems, where low-intensity

burning produced limited short-term changes in soil chemical properties [3,19,37]. The absence of a significant increase in soil pH, particularly the lack of post-fire alkalization, contrasts with the increases commonly reported after higher-intensity fires, which are often associated with the deposition of alkaline ash and the release of base cations during the combustion of organic matter [1,3]. In the present study, however, the maximum soil temperature recorded at 5 cm depth was only 35.8 °C, indicating limited heat transfer into the mineral soil. Such low thermal exposure provides a plausible explanation for the absence of detectable short-term changes in soil chemical properties.

The stability of SOM across treatments further suggests that the thermal exposure at 5 cm depth was insufficient to cause substantial thermal transformation or combustion of soil organic matter at this depth. The maximum temperature recorded in the soil (35.8 °C) was considerably lower than temperatures commonly associated with substantial thermal alteration of soil organic matter [1,2,38]. Consequently, the absence of significant changes in SOM is consistent with the limited penetration of heat into the soil profile during these experimental burns. This finding is particularly relevant for fire management in Andean ecosystems, where the conservation of soil organic matter contributes to soil fertility, structural stability, and the maintenance of soil ecosystem functions.

In contrast to the chemical properties, soil physical properties showed greater sensitivity to the experimental burning treatments. Upslope burning resulted in significantly lower bulk density and higher total porosity than both the unburned control and downslope-burning treatments. This response contrasts with the increase in bulk density and reduction in porosity frequently reported after high-intensity fires, which can result from the collapse of soil aggregates, combustion of organic matter, and subsequent structural reorganization [1,3,6,39]. In the present study, the low thermal exposure at 5 cm depth and the relatively short residence time associated with upslope burning likely limited these high-intensity processes. The observed increase in porosity and decrease in bulk density may therefore reflect a localized physical response of the surface soil to low-intensity burning rather than fire-induced structural degradation. However, in the absence of pre-burn baseline data for these specific plots, we cannot definitively attribute the observed decrease in bulk density solely to the thermal effects of the fire. Pre-existing plot variability, the presence of low-density residual ash or pyrogenic material on the soil surface, and minor soil disturbance or trampling during ignition remain plausible alternative explanations for this measurement taken only 24 h post-fire. Because soil physical properties were measured 24 h after burning, these differences should be interpreted as short-term post-fire responses; longer-term monitoring would be required to determine their persistence. Similar limited effects of prescribed low-intensity burning on soil physicochemical properties have been reported in Andean ecosystems [19].

4.2. Fire Behavior and Heat Transfer to the Ground

The significant differences in fire behavior between upslope and downslope burning are consistent with the influence of slope on fire propagation. Slope direction can affect fire rate of spread, with downslope propagation exhibiting distinct fire-spread dynamics [40]. In our experiment, upslope fires spread significantly faster and exhibited shorter heat residence times, whereas downslope fires spread more slowly and showed longer heat residence times. Rate of spread and flame-front residence time are important components of fire behavior, although their relationship may vary with fuel and fire conditions [41]. In our study, the contrasting spread rates and residence times between burning directions indicate that fire propagation relative to slope modified the temporal characteristics of thermal exposure.

The maximum soil temperatures recorded at 5 cm depth (29.2–35.8 °C in the burned plots) remained substantially below temperatures reported to reduce the survival of AMF propagules under experimental heating. Reductions in AMF propagule density have been observed following simulated fire, with soil temperatures reaching approximately 70 °C at 5 cm depth and stronger effects occurring closer to the soil surface [13]. Thus, the relatively low temperatures recorded in our experiment suggest that direct thermal damage to AMF propagules at 5 cm depth was likely limited. This interpretation is consistent with the low-intensity thermal conditions of the experimental burns and with the maintenance of soil mycorrhizal infectivity observed three months after fire.

4.3. Fire Intensity Context and Biological Significance of Soil Heating

A critical question arising from our results is whether the fire intensity generated in our experiment reflects the conditions experienced during natural wildfires in Andean ecosystems. We clarify that the fire behavior observed in our experimental burns was intentionally of low intensity, designed to mimic the frequent, low-intensity surface fires that have historically shaped these ecosystems, rather than the catastrophic, stand-replacing wildfires that have become increasingly common under climate change and land-use pressures. The fire behavior parameters recorded in our study—fire spread rates ranging from 0.64 to 1.17 m/min and heat residence times between 22.9 and 121 s—are characteristic of surface fires with low to moderate intensity. These values contrast sharply with those reported for high-intensity wildfires in tropical montane ecosystems, where fire spread rates can exceed 5 m/min and heat residence times can surpass 300 s [1,5].

The small but consistent increase in soil temperature at 5 cm depth observed in burned plots (ranging from 25.6 to 39.8 °C, compared to 20.8 °C in unburned controls) is biologically meaningful for several reasons. First, it indicates that the heat pulse generated by low-intensity burning was sufficient to affect surface soil properties—such as moisture content and the uppermost organic layer—but insufficient to sterilize the mineral soil or destroy the deeper AMF propagule bank. Second, this thermal buffering is precisely what explains the observed resilience of AMF infectivity following low-intensity burning: the temperatures recorded in our experiment are well below the lethal threshold for most AMF spores, which typically require sustained exposure to temperatures above 60–80 °C to experience significant mortality [13]. Third, the localized nature of this temperature increase suggests that AMF propagules located below the immediate surface layer, or those protected within soil aggregates, were largely shielded from direct thermal damage.

This interpretation contrasts sharply with the devastating effects of high-intensity wildfires reported in Mediterranean, boreal, and other fire-prone ecosystems, where soil temperatures at shallow depths can exceed 200–400 °C, causing complete mortality of both the AMF spore bank and the extraradical hyphal network [1,2,35]. In those systems, post-fire recovery of mycorrhizal communities often depends on long-distance dispersal from unburned refugia, a process that can take years to decades. Our results suggest that, under the low-intensity thermal conditions evaluated here, the AMF community retains sufficient functional capacity to support post-fire vegetation recovery without relying exclusively on external inoculum sources. This distinction has important implications for fire management in Andean ecosystems, where the conservation of belowground biological legacies may be key to ecosystem resilience.

4.4. Maintenance of Mycorrhizal Infectivity Following Low-Intensity Fire

The most relevant finding of this study was the tendency toward lower MSI_{50} values in burned plots, indicative of greater soil mycorrhizal infectivity, although differences among treatments were not statistically significant. Rather than indicating a fire-induced

stimulation of infectivity, these results suggest that AMF infective potential was maintained under the low-intensity thermal conditions of the experiment. Field evidence indicates that fire does not invariably lead to a persistent decline in AMF attributes. AMF abundance was not appreciably reduced along a post-fire chronosequence [42], whereas spore density, root colonization, and easily extractable glomalin in burned Cerrado soils recovered to levels comparable to those observed in unburned areas [15]. Collectively, these findings support the interpretation that AMF infective potential can persist or recover following fire and are consistent with the maintenance of infectivity observed under the low-severity thermal conditions of our experiment. This functional persistence may be ecologically relevant because AMF plays a fundamental role in regulating soil processes. Their positive effects on soil structure, nutrient cycling, and carbon sequestration contribute to the maintenance of resilient ecosystems [43].

To address the ecological context of these findings, it is important to consider whether the experimental fire intensity reflects natural conditions and if the observed thermal changes are biologically meaningful. The fire behavior recorded in this study (spread rates of ~0.8–1.0 m min^{-1} and residence times of ~49–121 s) is characteristic of low-intensity surface fires, which historically shape Andean shrublands, rather than catastrophic, stand-replacing wildfires. Furthermore, the modest increase in soil temperature at 5 cm depth (reaching means of 29.2–35.8 °C, compared to a 20.8 °C baseline) is biologically significant. While sufficient to alter some surface soil properties, these temperatures remain well below the lethal threshold for most AMF propagules (typically >60–80 °C). This thermal buffering explains the resilience of the AMF infective potential observed in our study, contrasting sharply with high-intensity wildfires where soil temperatures can exceed 200 °C, leading to complete sterilization of the upper soil profile.

However, preservation of infective potential does not imply that other components of the AMF community were unaffected by fire. Previous studies indicate that community-level responses may occur even when mycorrhizal function or persistence is maintained. Wildfire have been associated with short-term changes in the taxonomic and phylogenetic patterns of AMF followed by convergence toward unburned communities over longer post-fire periods [14]. Changes in AMF community organization have also been linked to fire-induced variation in soil conditions, including carbon and phosphorus availability [44]. Importantly, recent evidence suggests that compositional responses of mycorrhizal fungi to fire regime do not necessarily parallel changes in fungal functional attributes [45]. This distinction is particularly relevant to our study because MSI_{50} characterizes the capacity of the soil inoculum to initiate root colonization rather than AMF abundance, taxonomic identity, or community composition. Accordingly, the absence of a significant decline in infectivity should be interpreted as evidence that this specific functional capacity was maintained under the conditions evaluated, rather than as evidence that the AMF community remained unchanged. Moreover, because our bioassay was based on air-dried soil, the stability of MSI across treatments specifically suggests resilience of the AMF propagule bank—likely dominated by desiccation-tolerant spores, such as those of the family Glomeraceae—to low-intensity fire. This highlights that, although the immediate extraradical hyphal network may be affected by the combined effects of fire and sample processing, the underlying spore bank may remain intact and functional, thereby preserving the potential for post-fire mycorrhizal recovery.

4.5. Discussion on the Exploratory Relationships Between Fire Behavior, Soil Properties, and Post-Fire Mycorrhizal Infectivity

The correlation analyses revealed non-significant trends between fire behavior variables and MSI_{50}, but these must be interpreted with extreme caution. At $n = 6$, the statistical power

to detect meaningful associations is very low, and the observed correlation coefficients (e.g., $r_s = -0.50$ for heat residence time) fall well below the threshold required for significance ($|r_s| \geq 0.886$). Therefore, these patterns represent descriptive noise rather than evidence of functional relationships.

The negative direction of the correlation between heat residence time and MSI_0 is counterintuitive from a thermal stress perspective, as one would expect longer heating to reduce infectivity. However, given that soil temperatures at 5 cm depth remained well below the lethal threshold for AMF propagules (25.6–39.8 °C vs. the ~70 °C typically required for mortality [13], the observed trends likely reflect plot-to-plot variability rather than a causal effect of fire behavior on mycorrhizal infectivity. Accordingly, we present the 28–40 °C residence time metric strictly as a descriptive index of the duration of the flame front's passage over the soil surface, with no direct biological implication attached to AMF survival. Furthermore, the effects of soil heating depend not only on the temperature reached but also on the duration of heating [1,27], and under the minimal thermal conditions of this study, neither factor was sufficient to cause propagule mortality.

Soil moisture showed a weak positive correlation with MSI_0 ($r_s = +0.36$), which could suggest reduced mycorrhizal activity under wetter conditions due to limited soil aeration [42,44]. However, soil moisture was measured post-fire and cannot represent conditions during fire propagation, so this association should be regarded only as an exploratory pattern. Similarly, no significant relationships were detected between MSI_{50} and soil fertility variables (SOM, N, P, K), despite previous studies linking post-fire AMF community variation to these properties [14,40]. The absence of significant short-term changes in these soil variables under low-intensity burning likely limited the emergence of detectable relationships.

These exploratory trends warrant further investigation in studies with greater spatial replication, but they do not support management recommendations currently.

4.6. Implications for Fire Management in Andean Ecosystems

The results of this study reinforce the importance of fire intensity when evaluating potential belowground effects of fire in Andean ecosystems. Evidence from southern Ecuador shows contrasting soil responses across fire-intensity conditions. High-intensity wildfires in humid montane shrublands have been associated with substantial reductions in soil organic matter and several nutrients, together with increased soil compaction [5], whereas experimental low-intensity burns in Andean páramo produced no significant changes in soil physicochemical properties either shortly after fire or one year later [19]. Consistent with the latter pattern, the low-intensity burns evaluated here produced limited short-term effects on the measured soil properties and no detectable decline in AMF infective potential. Together, this regional evidence indicates that fire intensity should be explicitly considered when evaluating potential effects on soil ecological functions in Andean ecosystems.

From a management perspective, our findings indicate that the soil properties and AMF infective capacity evaluated here were maintained under the specific low-intensity experimental conditions, but they do not support a general recommendation for prescribed burning in Andean ecosystems. Fire behavior may also warrant consideration beyond peak soil temperature, because the effects of soil heating depend on both the magnitude and duration of thermal exposure [1]. In this context, heat residence time emerged from our exploratory analysis as a variable deserving further investigation. Integrating fire intensity and behavior with soil physicochemical properties and functional indicators of belowground biota may therefore provide a more robust basis for evaluating fire-management strategies in these ecosystems.

4.7. Limitations of the Study and Future Directions

The main limitations of this study were the small sample size ($n = 3$ per treatment) and the high within-treatment variability in MSI_{50} observed in the burned plots (CV > 40%), which limited the ability to detect treatment differences and relationships between mycorrhizal infectivity and fire or soil variables. This sample size is a limitation inherent to the logistical and ecological constraints of conducting experimental prescribed burns in fragile high-Andean ecosystems. While our local-scale study provides valuable mechanistic insights into the immediate effects of low-intensity fire on soil properties and AMF infectivity, extrapolating these findings to broader spatial scales or different ecological contexts should be done with caution. Local studies are essential for understanding fine-scale belowground processes, but they may not adequately predict broader landscape patterns due to the high spatial heterogeneity of montane soils and fire behavior. Consequently, correlations based on the six burned plots should be regarded as exploratory and require validation with greater spatial replication. We emphasize the need for future multi-site, landscape-level studies to validate and expand upon these localized patterns.

MSI_{50} provides a functional measure of the capacity of soil AMF propagules to initiate root colonization under standardized bioassay conditions but does not quantify colonization intensity, the relative abundance of individual AMF structures, or AMF taxonomic and community composition. Although we confirmed the presence of characteristic AMF structures (arbuscules, hyphal coils, vesicles, and aseptate hyphae) under a compound microscope to validate colonization (as detailed in Section 2.5), these were recorded as a binary response (colonized = 1, non-colonized = 0) to estimate MSI_{50}. This distinction is relevant because post-fire changes in AMF community composition may occur independently of functional responses [14,41], and the abundance of specific structures carries distinct functional implications: external hyphal colonization indicates soil exploration potential, vesicles denote long-term lipid storage, and arbuscules reflect active symbiotic nutrient exchange.

Finally, due to the small sample size ($n = 3$ per treatment) and high spatial variability (coefficients of variation frequently > 40%), this study had limited statistical power to detect moderate effect sizes. For MSI_{50}, the minimum detectable standardized effect with 80% power was approximately Cohen's f = 1.36. Similarly, for main soil variables (e.g., SOM, total N, available P), the high variability results in a large minimum detectable effect size. Therefore, the lack of statistical significance for these variables must be interpreted strictly as an "absence of evidence" of a treatment effect, rather than "evidence of absence". A study of this scale can fail to reject the null hypothesis, but it cannot definitively confirm that low-intensity burning has no ecological impact on soil chemistry or mycorrhizal infectivity. Additionally, while meteorological conditions (air temperature, relative humidity, wind speed, solar radiation, and zero precipitation) were logged during each burn (Supplementary Table S2), fuel load and fuel moisture content were not quantitatively assessed prior to ignition. These are critical drivers of fire behavior and soil heating, and their absence limits the ability to fully confirm that all experimental plots had perfectly comparable initial fuel conditions, representing a constraint in interpreting the fine-scale variability of fire behavior.

Future studies should therefore: (i) increase spatial replication to improve statistical power; (ii) complement infectivity assays with molecular characterization of AMF communities; (iii) incorporate detailed quantification of AMF root colonization structures (arbuscules, vesicles, and hyphae) to fully understand the functional dynamics of the persistent AMF community post-fire; (iv) incorporate repeated post-fire sampling to assess the temporal dynamics of functional and compositional responses; and (v) experimentally evaluate the effects of the magnitude and duration of soil heating on AMF infective po-

tential. These approaches would help determine whether the patterns observed here are reproducible and clarify the mechanisms underlying AMF responses to low-intensity fire.

5. Conclusions

Low-intensity experimental burns in an inter-Andean montane shrubland of southern Ecuador produced limited short-term effects on the measured soil properties. Soil chemical properties remained largely unchanged, whereas bulk density and porosity showed greater sensitivity to burning. Fire behavior differed between burning directions, with upslope fires spreading faster and downslope fires exhibiting longer heat residence times.

No significant reduction in AMF infective potential was detected three months after burning. Although burned plots showed descriptively median MSI_{50} values, differences among treatments were not statistically significant, supporting maintenance rather than enhancement of infective potential. No significant relationships between MSI_{50} and fire-behavior or soil variables were detected. These findings are restricted to the experimental conditions and ecosystem studied and should not be generalized to other fire severities or Andean ecosystems. Greater spatial replication, temporal monitoring, and molecular characterization of AMF communities are needed to assess the generality and persistence of these responses.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/jof12110823/s1. Figure S1: Representative micrographs of intraradicular structures observed in stained *Zea mays* roots during the soil infectivity bioassay. (A) intraradical hyphae, (B–D) mycorrhizal vesicles and arbuscules. Scale bars = 100 µm; Figure S2: Mean proportion of colonized *Zea mays* plants (%) across the soil dilution gradient in control, upslope-burning, and downslope-burning treatments. Error bars represent ± SE ($n = 3$ plots per treatment). The x-axis is displayed on a logarithmic scale; Figure S3: Spearman correlation matrix of fire behavior, soil physicochemical properties, and mycorrhizal soil infectivity (MSI_{50}) exclusively for the burned plots ($n = 6$). The upper triangle displays the correlation coefficients (r_s). Total porosity was excluded from this analysis to avoid perfect collinearity with bulk density. Color intensity reflects the magnitude and direction of the association (magenta = positive, blue = negative). Given the small sample size, none of the correlations reached statistical significance ($p > 0.05$ for all pairs, requiring $|r_s| \geq 0.886$), and thus no significance markers are displayed. The correlations between MSI_{50} and the four key variables (soil moisture, maximum soil temperature at 5 cm depth, heat residence time, and fire spread rate) are further illustrated as individual scatter plots in Supplementary Figure S2. These relationships should be interpreted strictly as exploratory trends; Figure S4: Exploratory scatter plots of plot-level MSI_{50} (raw estimates from Firth bias-reduced binomial logistic regression) against four key variables: (top-left) fire spread rate (ROS, m min^{-1}), (top-right) heat residence time at 5 cm soil depth (s), (bottom-left) soil moisture (%), and (bottom-right) maximum soil temperature at 5 cm depth (°C). Each point represents one burned plot ($n = 6$), colored by treatment (purple = downslope burning, orange = upslope burning). Dashed lines indicate the linear regression fit, with shaded gray bands representing the 95% confidence intervals. The Spearman correlation coefficients between MSI_{50} and each variable were weak to negligible ($r_s = -0.18$ for residence time, $r_s = 0.25$ for fire spread rate, $r_s = 0.12$ for soil moisture, and r = 0.23 for maximum soil temperature), and none reached statistical significance at $\alpha = 0.05$ (threshold $|r_s| \geq 0.886$ for $n = 6$). The wide confidence bands reflect the substantial uncertainty associated with the small sample size. These patterns are presented strictly as descriptive trends and do not support causal inferences or predictive relationships; Table S1: Plot-level estimates of Mycorrhizal Soil Infectivity 50 (MSI_{50}) and 95% confidence intervals obtained from Firth bias-reduced binomial logistic models. Slope and p-values describe the concentration–colonization relationship for each plot; Table S2: Summary of meteorological conditions recorded during the experimental burns for each treated plot. Values represent the mean ± standard deviation of measurements taken at multiple points along the central axis of each plot during fire propagation. Solar radiation was measured using a portable pyranometer (Apogee SP-110, USA; accuracy: ± 5%).

Precipitation was 0.0 mm across all plots during the burns. (Note: Unburned control plots P1, P5, and P9 are not included as they did not undergo experimental ignition).

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Abbreviations

The following abbreviations are used in this manuscript:

AMF	Arbuscular Mycorrhizal Fungi
MSI_{50}	Mycorrhizal Soil Infectivity 50 (soil proportion required for 50% host-plant colonization)
T_{max}	Maximum soil temperature at 5 cm depth
ROS	Rate of fire spread
SOM	Soil organic matter

References

1. Certini, G. Effects of Fire on Properties of Forest Soils: A Review. *Oecologia* **2005**, *143*, 1–10. [CrossRef] [PubMed]
2. Pellegrini, A.F.A.; Harden, J.; Georgiou, K.; Hemes, K.S.; Malhotra, A.; Nolan, C.J.; Jackson, R.B. Fire Effects on the Persistence of Soil Organic Matter and Long-Term Carbon Storage. *Nat. Geosci.* **2022**, *15*, 5–13. [CrossRef]
3. Keeley, J.E. Fire Intensity, Fire Severity and Burn Severity: A Brief Review and Suggested Usage. *Int. J. Wildland Fire* **2009**, *18*, 116–126. [CrossRef]
4. Neary, D.G.; Ryan, K.C.; DeBano, L.F. Wildland Fire in Ecosystems: Effects of Fire on Soil and Water. *Gen. Tech. Rep.* **2005**, *4*, 42.
5. Carrión-Paladines, V.; Hinojosa, M.B.; Jiménez Álvarez, L.; Reyes-Bueno, F.; Correa Quezada, L.; García-Ruiz, R. Effects of the Severity of Wildfires on Some Physical-Chemical Soil Properties in a Humid Montane Scrublands Ecosystem in Southern Ecuador. *Fire* **2022**, *5*, 66. [CrossRef]

6. Mataix-Solera, J.; Cerdà, A.; Arcenegui, V.; Jordán, A.; Zavala, L.M. Fire Effects on Soil Aggregation: A Review. *Earth-Sci. Rev.* **2011**, *109*, 44–60. [CrossRef]
7. Holden, S.R.; Gutierrez, A.; Treseder, K.K. Changes in Soil Fungal Communities, Extracellular Enzyme Activities, and Litter Decomposition Across a Fire Chronosequence in Alaskan Boreal Forests. *Ecosystems* **2013**, *16*, 34–46. [CrossRef]
8. van der Heijden, M.G.A.; Martin, F.M.; Selosse, M.-A.; Sanders, I.R. Mycorrhizal Ecology and Evolution: The Past, the Present, and the Future. *New Phytol.* **2015**, *205*, 1406–1423. [CrossRef] [PubMed]
9. Urgiles, N.; Loján, P.; Aguirre, N.; Blaschke, H.; Günter, S.; Stimm, B.; Kottke, I. Application of Mycorrhizal Roots Improves Growth of Tropical Tree Seedlings in the Nursery: A Step towards Reforestation with Native Species in the Andes of Ecuador. *New For.* **2009**, *38*, 229–239. [CrossRef]
10. Haug, I.; Setaro, S.; Suárez, J.P. Reforestation Sites Show Similar and Nested AMF Communities to an Adjacent Pristine Forest in a Tropical Mountain Area of South Ecuador. *PLoS ONE* **2013**, *8*, e63524. [CrossRef] [PubMed]
11. Haug, I.; Setaro, S.; Suárez, J.P. Species Composition of Arbuscular Mycorrhizal Communities Changes with Elevation in the Andes of South Ecuador. *PLoS ONE* **2019**, *14*, e0221091. [CrossRef] [PubMed]
12. Silva, D.; Kalinhoff, C.; Camargo-Mora, M.G.; Guerrero, O.A. Biomasa de raíces finas y micorrizas arbusculares en tres humedales altoandinos del sur de Ecuador con distinto grado de perturbación. *Ecosistemas* **2023**, *32*, 2429. [CrossRef]
13. Pattinson, G.S.; Hammill, K.A.; Sutton, B.G.; Mcgee, P.A. Simulated Fire Reduces the Density of Arbuscular Mycorrhizal Fungi at the Soil Surface. *Mycol. Res.* **1999**, *103*, 491–496. [CrossRef]
14. Xiang, X.; Gibbons, S.M.; Yang, J.; Kong, J.; Sun, R.; Chu, H. Arbuscular Mycorrhizal Fungal Communities Show Low Resistance and High Resilience to Wildfire Disturbance. *Plant Soil* **2015**, *397*, 347–356. [CrossRef]
15. Moura, J.B.; Souza, R.F.; Vieira-Júnior, W.G.; Lucas, L.S.; Santos, J.M.; Silva, S.D.E.; Marín, C. Effects of a Megafire on the Arbuscular Mycorrhizal Fungal Community and Parameters in the Brazilian Cerrado Ecosystem. *For. Syst.* **2022**, *31*, e001. [CrossRef]
16. Palta, Ş.; Özel, H.B.; Kanbur, S.; de Souza, T.A.F. Impact of Wildfire on Soil Characteristics and Arbuscular Mycorrhizal Fungi. *Environ. Monit. Assess.* **2024**, *196*, 681. [CrossRef] [PubMed]
17. Korb, J.E.; Johnson, N.C.; Covington, W.W. Arbuscular Mycorrhizal Propagule Densities Respond Rapidly to Ponderosa Pine Restoration Treatments. *J. Appl. Ecol.* **2003**, *40*, 101–110. [CrossRef]
18. Balaguer-Beser, A.; González, F.; Chuncho, C.G.; Carrión-Paladines, V.; Juela-Sivisaca, O. Altitudinal Variation in Fire Behavior in Andean Ecosystems in Southern Ecuador. *Fire Ecol.* **2026**, *22*, 46. [CrossRef]
19. Carrión-Paladines, V.; Fries, A.; Hinojosa, M.B.; Oña, A.; Álvarez, L.J.; Benítez, Á.; Rodríguez, F.L.; García-Ruiz, R. Effects of Low-Severity Fire on Soil Physico-Chemical Properties in an Andean Páramo in Southern Ecuador. *Fire* **2023**, *6*, 447. [CrossRef]
20. Homeier, J.; Werner, F.A.; Gradstein, S.R.; Breckle, S.W.; Richter, M. Flora and Fungi: Composition and Function. In *Gradients in a Tropical Mountain Ecosystem of Ecuador*; Beck, E., Bendix, J., Kottke, I., Makeschin, F., Mosandl, R., Eds.; Springer: Berlin/Heidelberg, Germany, 2008; pp. 87–100.
21. Coronel Alulima, T.N. Los sistemas agroecológicos de la parroquia San Lucas (Loja). Prácticas resilientes ante el cambio climático. *Let. Verdes. Rev. Latinoam. Estud. Socioambientales* **2019**, *26*, 191–212.
22. Valarezo Torres, G.E.; Carrión-Paladines, H.V.; Capa-Mora, E.D.; Jiménez Álvarez, L.S. Soil Quality/Health Indicators in a Disturbed Ecosystem in Southern Ecuador. *Soil Sci. Annu.* **2021**, *72*, 1–12. [CrossRef]
23. Soil Survey Staff. *Keys to Soil Taxonomy*, 12th ed.; U.S. Department of Agriculture, Natural Resources Conservation Service: Washington, DC, USA, 2014.
24. Hueso-González, P.; Martínez-Murillo, J.F.; Ruiz-Sinoga, J.D. Prescribed Fire Impacts on Soil Properties, Overland Flow and Sediment Transport in a Mediterranean Forest: A 5 year Study. *Sci. Total Environ.* **2018**, *636*, 1480–1489. [CrossRef] [PubMed]
25. Waldrop, T.; Goodrick, S. *Introduction to Prescribed Fires in Southern Ecosystems*; Science Update SRS-054; Department of Agriculture Forest Service, Southern Research Station: Asheville, NC, USA, 2012; 80p.
26. Geron, C.; Hays, M. Air Emissions from Organic Soil Burning on the Coastal Plain of North Carolina. *Atmos. Environ.* **2013**, *64*, 192–199. [CrossRef]
27. Santín, C.; Doerr, S.H. Fire Effects on Soils: The Human Dimension. *Philos. Trans. R. Soc. B Biol. Sci.* **2016**, *371*, 20150171. [CrossRef] [PubMed]
28. Bellgard, S.E.; Whelan, R.J.; Muston, R.M. The Impact of Wildfire on Vesicular-Arbuscular Mycorrhizal Fungi and Their Potential to Influence the Re-Establishment of Post-Fire Plant Communities. *Mycorrhiza* **1994**, *4*, 139–146. [CrossRef]
29. Plenchette, C.; Perrin, R.; Duvert, P. The Concept of Soil Infectivity and a Method for Its Determination as Applied to Endomycorrhizas. *Can. J. Bot.* **1989**, *67*, 112–115. [CrossRef]
30. Leal, P.L.; Stürmer, S.L.; Siqueira, J.O. Occurrence and Diversity of Arbuscular Mycorrhizal Fungi in Trap Cultures from Soils under Different Land Use Systems in the Amazon, Brazil. *Braz. J. Microbiol.* **2009**, *40*, 111–121. [CrossRef]
31. Phillips, J.M.; Hayman, D.S. Improved Procedures for Clearing Roots and Staining Parasitic and Vesicular-Arbuscular Mycorrhizal Fungi for Rapid Assessment of Infection. *Trans. Br. Mycol. Soc.* **1970**, *55*, 158-IN18. [CrossRef]

32. Soil Survey Staff. *Soil Survey Field and Laboratory Methods Manual*; Soil Survey Investigations Report No. 51; Version 2 (2014); U.S. Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Center: Lincoln, NE, USA, 2014.
33. Walkley, A.; Black, I.A. An Examination of the Degtjareff Method for Determining Soil Organic Matter, and a Proposed Modification of the Chromic Acid Titration Method. *Soil Sci.* **1934**, *37*, 29–38. [CrossRef]
34. Bray, R.H.; Kurtz, L.T. Determination of Total, Organic, and Available Forms of Phosphorus in Soils. *Soil Sci.* **1945**, *59*, 39–46. [CrossRef]
35. Firth, D. Bias Reduction of Maximum Likelihood Estimates. *Biometrika* **1993**, *80*, 27–38. [CrossRef]
36. Heinze, G.; Schemper, M. A Solution to the Problem of Separation in Logistic Regression. *Stat. Med.* **2002**, *21*, 2409–2419. [CrossRef] [PubMed]
37. Yangua-Solano, E.; Carrión-Paladines, V.; Benítez, Á. Effects of Fire on Pyrodiversity of Terricolous Non-Tracheophytes Photoautotrophs in a Páramo of Southern Ecuador. *Diversity* **2023**, *15*, 1176. [CrossRef]
38. Knicker, H. How Does Fire Affect the Nature and Stability of Soil Organic Nitrogen and Carbon? A Review. *Biogeochemistry* **2007**, *85*, 91–118. [CrossRef]
39. DeBano, L.F. The Role of Fire and Soil Heating on Water Repellency in Wildland Environments: A Review. *J. Hydrol.* **2000**, *231–232*, 195–206. [CrossRef]
40. Sullivan, A.L.; Sharples, J.J.; Matthews, S.; Plucinski, M.P. A Downslope Fire Spread Correction Factor Based on Landscape-Scale Fire Behaviour. *Environ. Model. Softw.* **2014**, *62*, 153–163. [CrossRef]
41. Wotton, B.M.; Gould, J.S.; McCaw, W.L.; Cheney, N.P.; Taylor, S.W. Flame Temperature and Residence Time of Fires in Dry Eucalypt Forest. *Int. J. Wildland Fire* **2011**, *21*, 270–281. [CrossRef]
42. Treseder, K.K.; Mack, M.C.; Cross, A. Relationships among Fires, Fungi, and Soil Dynamics in Alaskan Boreal Forests. *Ecol. Appl.* **2004**, *14*, 1826–1838. [CrossRef]
43. Wahab, A.; Muhammad, M.; Munir, A.; Abdi, G.; Zaman, W.; Ayaz, A.; Khizar, C.; Reddy, S.P.P. Role of Arbuscular Mycorrhizal Fungi in Regulating Growth, Enhancing Productivity, and Potentially Influencing Ecosystems under Abiotic and Biotic Stresses. *Plants* **2023**, *12*, 3102. [CrossRef] [PubMed]
44. Cheng, Z.; Wu, S.; Du, J.; Liu, Y.; Sui, X.; Yang, L. Reduced Arbuscular Mycorrhizal Fungi (AMF) Diversity in Light and Moderate Fire Sites in Taiga Forests, Northeast China. *Microorganisms* **2023**, *11*, 1836. [CrossRef] [PubMed]
45. Maerowitz-McMahan, S.; Gordon, C.E.; Nolan, R.H.; Matta, P.; Montalban de la Mata, A.; Powell, J.R. Decoupled Responses of Mycorrhizal Fungal Communities and Function to Recurrent Wildfire. *Soil Biol. Biochem.* **2026**, *214*, 110070. [CrossRef]

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