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Original article

Fuel loading and flammability for a páramo area in southern Ecuador

Carga de combustible y su inflamabilidad para un área de páramo en el sur de Ecuador

Carga de combustível e inflamabilidade para uma área de páramo no sul do Equador

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SUMMARY

The characterization of plant fuels present in Ecuador's paramos is a key task for initiating integrated fire management activities. This research aimed to determine plant fuel loading and flammability in a páramos area in southern Ecuador. Shrub, herbaceous, and dead fuels were evaluated. Estimates were made using a direct method

in three 0.25 m2 subplots systematically distributed across a 4 m2 plot · Fuel samples were collected and transported to the laboratory for drying. The ratio of wet to dry weight of the samples allowed for the calculation of the conversion factor, which was used to estimate fuel loading. For flammability, dry samples of 5 g were selected, with 20 replicates per fuel. Using the direct flame method, ignition time, sustainability, flame height, combustibility, and flammability category were calculated. The páramo's fuel load was 8.2 hta ^{1}, with 47.2% of the fuel content being dead, 40.1% herbaceous, and 12.7% shrubby. The flammability category for all three fuel types was very extremely flammable. The herbaceous component was most representative in terms of ignition time, flame height, and combustibility; while the shrub component stood out in terms of sustainability. The páramo has a significant fuel load and is classified as very extremely flammable, making this ecosystem highly flammable and susceptible to wildfires.

Keywords: biomass; fire behavior; floral diversity; forest fires; fire regime.

RESUMEN

La caracterización de combustibles vegetales presentes en los páramos del Ecuador constituye una tarea clave para dar inicio a actividades sobre el manejo integral del fuego. Esta investigación se propuso determinar la carga del combustible vegetal y su inflamabilidad en un área de páramo en el sur de Ecuador. Se evaluaron los combustibles arbustivos, herbáceos y muertos. Las estimaciones se realizaron mediante un método directo en tres subparcelas de 0,25 m^2 distribuidas sistemáticamente en una parcela de 4 m^2. Se colectaron muestras de los combustibles, que fueron movilizadas al laboratorio para el respectivo secado. La relación entre peso húmedo y seco de las muestras permitió calcular el factor de conversión que sirvió para estimar la carga de combustible. Para la inflamabilidad se seleccionaron muestras secas de 5 g, con 20 repeticiones por combustible, y con el método de llama directa se calculó el tiempo de ignición, sostenibilidad, altura de la llama, combustibilidad y la categoría de inflamabilidad. La carga de combustible del páramo fue de 8,2 hta^{1}, donde el 47,2 % fue muerto, 40,1 % herbáceo y 12,7 % arbustivo. La categoría de inflamabilidad de los tres tipos de combustibles fue muy extremadamente inflamable. El componente herbáceo fue más representativo en cuanto a tiempo de ignición, altura de llama y combustibilidad;

mientras que, el componente arbustivo sobresalió en la sostenibilidad. El páramo presenta una importante carga de combustibles y una categoría de muy extremadamente inflamable, lo que convierte a este ecosistema como altamente inflamable y susceptible a los incendios forestales.

Palabras clave: biomasa; comportamiento del fuego; diversidad florística; incendios forestales; régimen del fuego.

RESUMO

A caracterização dos combustíveis vegetais presentes nos páramos do Equador constitui uma tarefa chave para dar início às atividades de manejo integral do fogo. Nesse contexto a pesquisa teve como objetivo determinar a carga de combustível vegetal e sua inflamabilidade numa área de páramo no sul do Equador. Foram avaliados os combustíveis arbustivos, herbáceos e mortos. As estimativas foram realizadas por meio do método direto em três subparcelas de 0,25 m², distribuídas sistematicamente em uma parcela de 4 m². Amostras dos combustíveis foram coletadas e transportadas ao laboratório para secagem. A relação entre o peso úmido e seco das amostras permitiu calcular o fator de conversão utilizado para estimar a carga de combustível. Para a avaliação da inflamabilidade, foram selecionadas amostras secas de 5 g, com 20 repetições por tipo de combustível; utilizando o método de chama direta foram determinados o tempo de ignição, a sustentabilidade da chama, a altura da chama, a combustibilidade e a categoria de inflamabilidade. A carga de combustível do páramo foi de 8,2 t ha^{-1}, sendo 47,2% de material morto, 40,1% herbáceo e 12,7% arbustivo. A categoria de inflamabilidade dos três tipos de combustível foi classificada como extremamente inflamável, com o componente herbáceo se destacando no tempo de ignição, altura da chama e combustibilidade; enquanto o componente arbustivo apresentou maior sustentabilidade da chama. O páramo apresenta uma carga significativa de combustíveis e uma categoria de inflamabilidade extremamente elevada, o que torna este ecossistema altamente inflamável e suscetível a incêndios florestais.

Palavras-chave: biomassa; comportamento do fogo; diversidade florística; incêndios florestais; regime do fogo.

INTRODUCTION

Plant fuels are part of the composition and structure of every ecosystem and are the only element of the fire triangle that humans can manipulate through prescribed burning (Nguyen *et al.,* 2025; Weston *et al.,* 2022; Gomes *et al.,* 2020; Garrido *et al*., 2016; Ramos Rodríguez, 2010). Various investigations have characterized fuels by quantity or loading, flammability, spatial, horizontal and vertical distribution, fuel type, density, and moisture content (Ramos Rodríguez, 2010; Skowronski *et al.,* 2020).

Plant fuel refers to the living and dead organic material present in an ecosystem in different forms and quantities, generally expressed in tons per hectare or kilograms per m^2, and which when in contact with fire turns into smoke and ash (Nguyen *et al.,* 2025; Skowronski *et al.,* 2020; Ramos Rodríguez, 2010). It is considered a fundamental element for the occurrence and spread of fire and determines the amount of heat that will be released during burning according to the amount of existing fuel and its flammability.

Flammability is a characteristic of fuels determined by the physiological, physical, and chemical characteristics of plants; and is related to the ease with which they ignite and sustain a fire (Jian *et al.,* 2024). Its estimation has mainly been based on the time at which the flame starts, although other researchers have also incorporated other variables such as flame duration and burning speed after ignition (Hachmi *et al*., 2011). Its study, whether at the species or ecosystem level, is crucial for preventing and combating forest fires, since it would allow predicting fire behavior based on the presence of different types of fuels.

Given the evident importance of fuels in ecosystems and their role in fire behavior, there are few studies related to fuels in Andean ecosystems in Ecuador, creating a significant gap between comprehensive fire management, ecosystem conservation, and area safety. This is why, when fires are not controlled, they spread and destroy natural ecosystems, causing biodiversity loss, altering species composition, and facilitating the establishment

of invasive species (Kelly *et al.,* 2020), with no immediate responses for their prevention and control.

Fire-related research in southern Ecuador has increased significantly in recent years; and, mainly, on forest fuels and flammability, studies focus on determining live and dead forest fuel loads and their flammability in native forest and scrubland (Coronel, *et al* ., 2024; Muñoz-Chamba *et al*., 2023). At the landscape level, it is necessary to complete the knowledge of fuels and their flammability in fragile and susceptible ecosystems such as the southern Andean páramos, which provide important ecosystem services such as flow regulation and generation, present in their floristic compositions important abundances of woody species and a high abundance of species of the genus Puya (Hofstede *et al*., 2023).

Forest fires, which in Ecuador are caused 96% by anthropogenic activities and 4% by natural causes (Neger, 2021), and constitute a threat to these fragile ecosystems (Hofstede *et al*., 2023). The páramo under study corresponds to an ecosystem affected by different forest fires that have occurred in the last 20 years, which has led to its recognition as an anthropogenic páramo, characterized by the alteration of its floristic composition and with it, a series of ecological processes such as alteration of biogeochemical cycles, reduction of water infiltration into the soil, and increase in erosive processes, which in turn has led to the appearance and dominance of aggressive or invasive species such as plants of the genus *Pteridium* (Tillaguango-Pintado *et al*., 2023).

Under this context, the research aimed to determine the content of the plant fuel load (live and dead) and its flammability in a páramo area in southern Ecuador, which is considered susceptible to the occurrence of forest fires (Sarango-Cobos, *et al*., 2019; Muñoz-Chamba, *et al*., 2023).

MATERIALS AND METHODS

Study site

The anthropic páramo is located in the upper part of the Francisco Vivar Castro University Park (PUFVC), south of Ecuador, in the city, canton and province of Loja. The climatic characteristics associated with the place are a rainy temperate climate, with an annual precipitation of 955 mm, average annual temperature of 16.6° C, relative humidity of 71.96%, average evaporation of 111.33 mm, wind speed between 3.64 to 5.44 m/s (Aguirre, *et al*., 2016).

The altitudinal range where the anthropic páramo is located is between 2300 and 2468 m asl, with an approximate area of 20.58 ha. The terrain has slopes greater than 35%, with few areas with an undulating relief located in the upper part. This ecosystem has undergone modifications in the structure and composition of its vegetation (Aguirre and Yaguana, 2014). The dominant species in the case of herbs are *Calamagrostis intermedia* (J. Presl) Steud., *Pteridium esculentum* (G.Forst.) Cockayne and *Baccharis sagittalis* DC., and among the shrub species, *Baccharis latifolia* Pers., *Hypericum laricifolium* Juss. and *Gynoxys nítida* Muschl stand out (Figure 1).

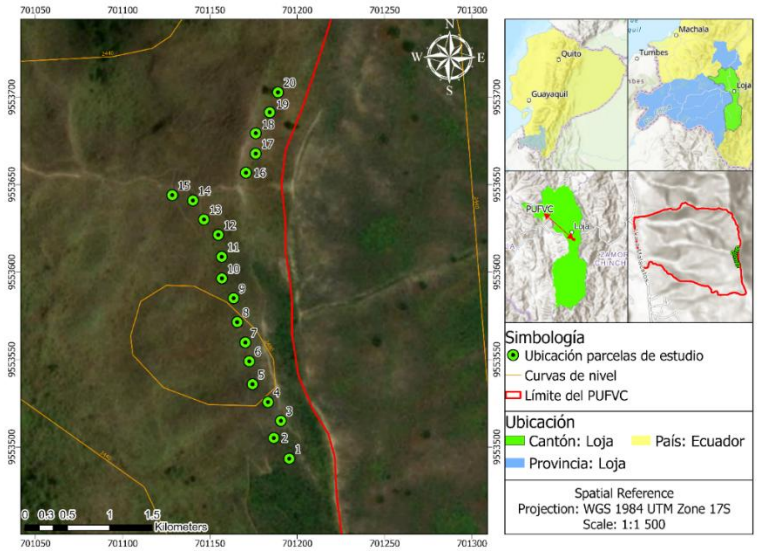

Figure 1. *- Location of the Francisco Vivar Castro University Park and the study units in the anthropic páramo*

Design, number and size of samples

To assess fuel load in the upper part of the anthropic páramo and ensure representative coverage of the sampled area, a systematic sampling design was implemented in a linear section of 200 m. In this section, 20 temporary plots of 4 m^2, distributed equidistantly every ten meters, ensuring a homogeneous distribution in the study area. This design adequately captured the spatial variability of total plant fuel (herbaceous, shrubby, and dead), with a relative error allowed of 15%, confirming that the number of plots used was statistically representative. A z value of 1.96, an allowable error of 15%, and a coefficient of variation of 33.95% were used for its calculation.

The flammability of the three fuel types was analyzed using a completely randomized design. From a total of 100 dry grams per fuel type, 20 tests were conducted using five-gram samples of dry material per fuel. The number of replicates was based on the study by Hachmi *et al.* (2011), who demonstrated that reducing the number of tests in flammability tests they conducted with forest species (50, 36, 24, and 12) does not significantly affect the accuracy of the results, and they were able to work with up to 12 samples.

Fuel load estimation

The estimated fuel load was for living material (shrubs and herbs) and dead material (litter). Prior to collecting fuel types, the floristic composition of the study site was determined, differentiating between herbs and shrubs.

The estimation was carried out using a direct or destructive method, which consisted of the extraction and collection of all fuel types studied. Therefore, to reduce the impact on the vegetation and soil of the anthropic páramo within the 4 m^2 areas, it was necessary to subsample the material in three 50 × 50 cm subplots distributed diagonally within each 4 m^2 plot.

In each 50 × 50 cm subplot, shrub, herbaceous, and dead fuel were separated, and the wet weight (g) was recorded. The three samples were then mixed by fuel type, yielding a composite sample of 1,000 grams. These samples were then transported to the Plant

Physiology Laboratory and placed in a circular air oven at a temperature of 55 ± 1°C until the weight stabilized.

Subsequently, a conversion factor was determined by fuel type (Ayala *et al*., (2014), which was obtained from the ratio of the dry and wet weight of the samples. This factor was used to obtain the dry fuel load (Table 1).

Table 1. *- Formulas used for estimating dry plant fuel content*

Fuel type	Formula
Shrubby	Cara de combustible = Peso húmedo $_{\text{arbusto}} * r$
Herbaceous	Cara de combustible = Peso húmedo $_{\text{hierba}} * r$
Dead	Cara de combustible = Peso húmedo $_{\text{hojarasca}} * r$

Source : Ayala et al. (2014)

Estimation of flammability

Flammability was determined under laboratory conditions, considering combustible materials such as leaves and twigs smaller than or equal to 6 mm in diameter. Prior to calculating flammability characteristics, the moisture content on a wet basis was determined by fuel type.

The flammability characteristics were evaluated using the direct flame method, which consisted of placing a sample on a 22 × 15 cm mesh, extended horizontally. The flame was applied directly to the fuel until it ignited. The flammability characteristics evaluated were: ignition time, sustainability, combustibility, burnability and maximum flame height (Hachmi *et al* ., 2011). The flammability category was determined based on the flammability index (FI) with the formula proposed by Hachmi *et al*. (2011), which uses the ignition time (TI), sustainability (TC) and maximum flame height (FH) equation 1.

$$FI = \left[\frac{TC + 30 - \frac{TI}{2}}{TI + 10}\right] EXP\left[\frac{FH}{FH + 40}\right]^2 \quad (1)$$

The interpretation of the flammability category was based on the flammability index values, which were: when FI < 0.5 the category was very slightly flammable; 0.5 ≤ FI < 1.5 slightly flammable; 1.5 ≤ FI < 2.5 moderately flammable; 2.5 ≤ FI < 3.5 flammable; 3.5 ≤ FI < 4.5 extremely flammable; 4.5 ≤ FI very extremely flammable.

Analysis of information

For fuel loading and flammability characteristics, comparisons were made between the three fuel types. Nonparametric methods such as Kruskal-Wallis were applied, as the assumptions of normality and homoscedasticity of variance were not met. Furthermore, since statistical significance existed between fuel types, the Wilcoxon test was applied with a significance level of 0.05. Statistical analysis was performed using RStudio 4.2.2 software.

RESULTS AND DISCUSSION

Live and dead fuel loading

The total fuel load in the anthropic páramo was 8.2 t ha $^{-1}$, where live fuel (herbaceous and shrubby) represented 52.8 % of the total, and dead fuel constituted 47.2 % (Table 2). According to the Kruskal-Wallis test, there were significant differences between the three fuel types ($p = 0.0001$; $\alpha = 0.05$), where herbs and dead fuel differed from shrubs with the highest loads (Figure 2).

Table 2. *- Statistics of fuel loads for the herbaceous, shrub and dead strata of the PUFVC, from October to December 2023*

Statistics	Herbaceous fuel	Bush fuel	Dead fuel
Average fuel load (t ha $^{-1}$)	3.29	1.04	3.87
Number of observations	20	20	20
Representativeness (%)	40.1	12.7	47.2
Median (t ha $^{-1}$)	3.33	0.73	3.74
Minimum (t ha^{-1})	1.00	0.17	1.18

Maximum (t ha^{-1})	7.46	3.48	7.99
Standard deviation (t ha^{-1})	± 1.47	± 0.89	± 1.79
Standard error (t ha^{-1})	± 0.33	± 0.20	± 0.40
Statistical significance according to Wilcoxon test, α = 0.05	to	b	to

Note: Different letters indicate significant differences.

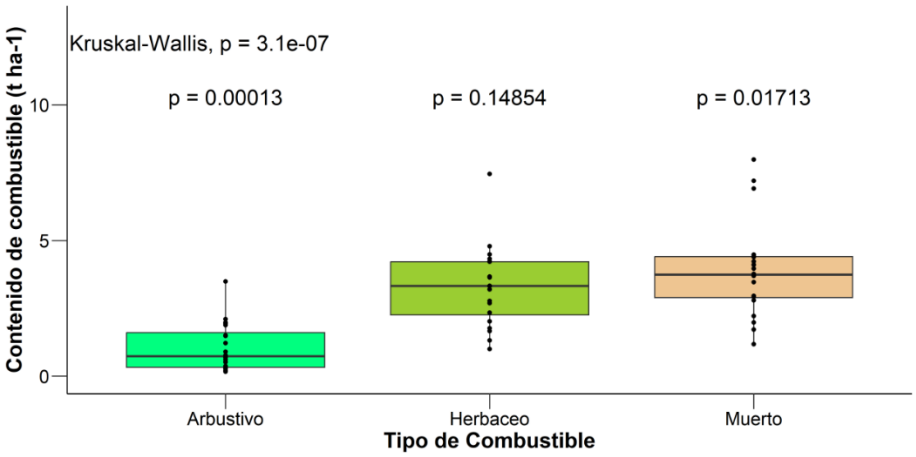

Figure 2. *- Comparison of the loads of the three types of fuels studied in the anthropic páramo of the PUFVC, October to December 2023*

The fuel load reported for the anthropogenic páramo of the PUFVC can be compared with other intervened páramo in Colombia (Torres *et al*., 2012), with values ranging from 3.46 t ha^{-1} to 7.62 t ha^{-1}; while in conserved páramo of the Podocarpus and Sangay National Park in Ecuador, the fuel load was 9.35 t ha^{-1} (Urgiles *et al*., 2018) and 13.1 t ha^{-1} respectively (Cargua *et al*., 2014), values that are considered higher than the páramo studied. These results reinforce the idea that anthropogenic activities significantly decrease the fuel load in páramo.

Living fuels were most represented in the anthropic páramo, with 40.1% herbs and 12.7% shrubs. Apparently, this pattern is commonly observed in intervened and conserved páramo (Urgiles *et al*., 2018; Torres *et al*., 2012), because in páramo the herbaceous stratum from 3000 m asl is the most representative, although the diversity and composition may vary depending on altitude, slope orientation, and the influence of environmental factors (Zheng *et al*., 2022).

On the other hand, in the case of dead fuels, the load reported for the PUFVC (3.87 t ha ^{1}) was lower than that of the páramos conserved in the Podocarpus National Park (5.42 t ha^{-1}) (Urgiles *et al*., 2018) and Sangay (112.16 t ha^{-1}) (Cargua *et al*., 2014). However, its representativeness in the anthropic páramos was high, being among those with the highest load, which could be due to the various impacts that occurred, such as the case of forest fires that occurred in the PUFVC in previous years. This has undoubtedly given way to the establishment of aggressive pioneer species such as *Baccharis latifolia* (Aguirre *et al* ., 2019) and species of the genus *Pteridium* , mainly the latter, which is characterized by providing significant amounts of dead biomass (Valdez-Ramírez *et al* ., 2020).

Flammability of live and dead fuel

The flammability of herbaceous, shrubby, and dead fuels was determined at moisture contents ranging from 20% to 56%, with statistical differences between these (Kruskal-Wallis; p= 0.000; α= 0.05) (Table 3). This characteristic of fuels is one of the most important in fire processes, as it directly influences ignition and spread, and also determines the extent to which a fuel can be consumed (Kane and Prat-Guitart, 2020) . The presence of moisture in the studied fuels was variable, which could be influenced by factors such as plant physiological characteristics, fuel structure, and climatic conditions (Ferrer *et al*., 2022; Alzate-Guarín *et al* ., 2022 ; Bar-Massada and Lebrija-Trejos, 2021; Rosales-Solórzano, 2020 ; Zylstra *et al* ., 2016). The three types of fuels studied were located in the very extremely flammable category (Table 3); however, their differences can be analyzed or compared by the estimated characteristics such as ignition time, sustainability, flame height, and combustibility.

Table 3. *- Statistics of the flammability characteristics for herbaceous, shrubby and dead fuels of the anthropic moor of the PUFVC*

Variable	Unit	Dead fuel	Herbaceous fuel	Bush fuel
Average moisture content	%	20:11 a	46.1 5 b	55.00 c
Average ignition time	S	4.85 ab	4.11 a	6.35 b
Average sustainability	S	49.05 b	40.65 to	80.50 b

Average maximum flame height	Cm	40.40 b	66.05 a	50.70 c
Average combustibility	g/s	0.05 b	0.11 to	0.09 b
Flammability category	Category	Very extremely flammable	Very extremely flammable	Very extremely flammable

Note: Equal letters indicate statistical significance, according to the Wilcoxon test (a = 0.05).

For the ignition time, the values were between 1 s and 15 s, with herbaceous fuel being distinguished by the fastest values (Table 3), which is supported by Burger and Bond (2015) who mention that these ignite more quickly because they are made up of fine and light material less than 6 mm in diameter. In the particular case of the origin of the fuels, that is, the species, they could explain the values reported for herbs, since, for example, the Ericaceae and Asteraceae families, which were the most representative in the anthropic moorland, present flammable chemical and phenolic compounds in their structure, which is ratified by Guerrero *et al*. (2021) who mention that the presence of phenols and essential oils favor the presence of flame in fast times. Additionally, chemical compounds belonging to the group of terpenes and aromatic compounds derived from phenylpropane are recorded in species of the Ericaceae family (Pandey *et al* ., 2017; Kiran and Prakash, 2015 ; Mitic *et al*., 2018 ; Matulevich and Gil, 2014) ; likewise, species of the Asteraceae family have great phytochemical importance and structures that produce and secrete different chemical compounds, among which pectic, lipid, tannin and steroidal compounds stand out (Tosoratto *et al*., 2016) that accelerate ignition times, as is the case of phenylpropane, which is flammable at 30 ° C. In this sense, the flammability of living fuel, mainly the foliar part, is influenced by a wide range of chemical compounds that require a deeper understanding for adequate planning in fire management (Guerrero *et al*., 2024).

Sustainability ranged from 20 s to 144 s, with differences between fuels (Kruskal-Wallis, p= 0.000; α= 0.05), with shrubs having the longest flame duration standing out, although these were not different from the values reported for dead fuels (Table 3).

In the case of flame height, values ranged from 20 cm to 85 cm, with statistically significant differences between fuels (Kruskal-Wallis; p= 0.000; α= 0.05), with grasses having the highest values. This particularity reported for the anthropic páramo could be explained by the small size of the leaves of the grasses, which is corroborated by Popović *et al*. (2021), who mention that thin and long leaves in grasses induce high flames (herbaceous stratum).

For combustibility, values between 0.03 gs $^{-1}$ and 0.21 gs -1 were recorded, with statistical differences between fuels (Kruskal-Wallis; p= 0.000; α= 0.05), with grasses and dead fuel standing out with the highest values.

When comparing the reported values for flammability characteristics such as ignition time, sustainability, flame height, and combustibility with other research such as Coronel *et al*. (2024), Muñoz-Chamba *et al*. (2023), Alzate-Guarín *et al*. (2022), De Magalhães and Schwilk (2012), a high variability is observed, which could be a response to the influence of factors such as the size of the fuels analyzed, the estimation methods used, the amount of plant material used, moisture content, and the origin of the fuel. According to Popović *et al*. (2021), plant characteristics significantly influence the flammability of species, impacting ecosystem dynamics and planning towards sustainable fire management.

Regarding the origin of the fuel, the most representative herbs were *Calamagostris intermedia, Baccharis sagitalis* and *Pteridium esculentum,* which at the time of the flammability tests consumed all the samples, while in the case of *Puya parviflora* it showed greater resistance in the rosette of the plant with high release of embers.

The results of the present study, in terms of the flammability characteristics and the category recorded for the three types of fuels in the anthropic páramo, would allow us to infer that it is a flammable ecosystem. This undoubtedly reinforces the idea that the anthropic páramo is susceptible to forest fires (Tillaguango-Pintado *et al*., 2023), that anthropogenic processes related to fire bring about the regeneration of exotic woody species such as *Pinus patula* and other flammable species, especially in controlled burns (Amoako *et al*., 2023), effects on soil properties (Beltrán-Pineda and Lizarazo-Forero,

2013 ; Camargo-García, *et al* ., 2012), threatening diversity and endemism (Matson and Bart, 2013) .

CONCLUSIONS

The fuel load determined in the anthropic páramo of the PUFVC is represented mostly by dead fuel (47.2%) and herbaceous fuel (40.1%), and to a lesser extent by shrub fuel (12.7%), constituting the basis for future monitoring and adequate fuel management in comprehensive fire management.

The flammability characteristics of the three fuel types (herbaceous, shrubby, and dead) varied in terms of ignition time, sustainability, flame height, and combustibility, with herbaceous fuels being the most prominent, followed by dead fuels. The flammability category determined for all three fuel types was very extremely flammable, suggesting that the anthropogenic páramo is a flammable ecosystem and, therefore, susceptible to forest fires.

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