Article

Not peer-reviewed version

Climate-Driven Wildfire Risk in the Sumapaz Páramo, Colombia: Coupling the Fire Weather Index with Spatiotemporal Analysis

Karel Aldrin Sánchez Hernandez * , Valentina Ortiz Plazas , Andrés Quiroga Hernandez ,
Hernán Dario Granda Rodriguez

Posted Date: 23 March 2026

doi: 10.20944/preprints202603.1832.v1

Keywords: vegetation cover fire; wildfire; Fire Weather Index; IDEAM risk zoning; Sumapaz Páramo; climatic variability; risk management

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 23 March 2026 doi:10.20944/preprints202603.1832.v1

Article

Climate-Driven Wildfire Risk in the Sumapaz Páramo, Colombia: Coupling the Fire Weather Index with Spatiotemporal Analysis

Karel Aldrin Sánchez Hernandez *, Valentina Ortiz Plazas, Andrés Quiroga Hernandez and Hernán Darío Granda Rodriguez

Cundinamarca Agroenvironmental Research Group, Environmental Engineering Program, Faculty of Agricultural Sciences, Universidad de Cundinamarca, Fusagasugá, Cundinamarca, 252211, Colombia
* Correspondence: kasanchez@ucundinamarca.edu.co

Abstract

Vegetation Cover Fires (VCFs) are recurring disturbances that threaten biodiversity, hydrological regulation, and carbon storage. Between 2001 and 2023, 128 fire events consumed approximately 815 ha in Sumapaz, representing 64.9% of all fires recorded across Bogotá's 20 localities. Despite this disproportionate impact, no spatially explicit, operational risk management framework has been available for the region. This study addresses that gap by proposing an integrated risk assessment and management strategy based on (i) the Canadian Forest Fire Danger Rating System Fire Weather Index (FWI), derived from ERA5 reanalysis climate data; (ii) spatial and temporal hot-spot analysis of MODIS FIRMS active-fire detections; and (iii) IDEAM's multi-component Vulnerability and Threat scoring protocol. Spatial data were processed using ArcGIS, and FWI sub-indices were computed for each month of the 2001–2023 period. The FWI averaged 0.78 (low danger) across the study period yet peaked at 13.7 in February 2010 (moderate-to-high danger), consistent with the year of highest recorded fire activity (19 events). High and very high-risk areas (3.70% combined) coincide with slopes >25%, the presence of the invasive and pyrogenic *Ulex europaeus*, and proximity to populated and agricultural lands. The study concludes with a three-pillar risk management framework risk knowledge, risk reduction, and disaster management providing spatially targeted, operationally viable strategies for local and institutional actors. Limitations regarding MODIS detection uncertainty, ERA5 spatial resolution in complex terrain, and the need for probabilistic modelling are explicitly acknowledged.

Keywords: vegetation cover fire; wildfire; Fire Weather Index; IDEAM risk zoning; Sumapaz Páramo; climatic variability; risk management

1. Introduction

1.1. The Current State of Wildfires in Sumapaz and the Governance Gap

The Sumapaz locality — Bogotá's District 20 and the world's largest continuous páramo ecosystem — is facing a persistent and escalating wildfire problem. Official records from Bogotá's Distrito Commission for Forest Fire Prevention and Mitigation (CDPMIF) document 197 vegetation cover fire (VCF) events across the capital between 2001 and 2023, of which 64.9% occurred in Sumapaz alone, burning approximately 815 ha [1,2]. Peak years — 2001, 2003, 2004, and 2010 — reflect a close temporal alignment with periods of anomalously low precipitation and elevated temperatures associated with El Niño–Southern Oscillation (ENSO) warm phases. Despite this well-documented fire burden, Sumapaz currently lacks a spatially explicit, operationally integrated risk management framework that accounts for the region's complex topography, distinct microclimates, and the growing threat of pyrogenic invasive species [3,4].

Existing management approaches in Colombia rely primarily on the IDEAM (Instituto de Hidrología, Meteorología y Estudios Ambientales) national protocol for VCF risk zoning, which uses static vegetation susceptibility maps at a scale of 1:100,000 [5]. While this protocol provides a nationally consistent baseline, it does not incorporate real-time or seasonal meteorological fire danger indices, limiting its operational utility. The Local Risk Management and Climate Change Plan (CLGR-CC) for Sumapaz identifies wildfires as the dominant risk scenario but acknowledges an absence of detailed diagnostic tools and prevention strategies [6]. This study directly responds to that documented gap.

1.2. Vegetation Cover Fires (VCFs): Definition and Global Context

In the Colombian regulatory framework, the term 'Incendios de Cobertura Vegetal' (ICV) — translated here as Vegetation Cover Fires (VCFs) — refers specifically to uncontrolled fires that consume any type of vegetation layer, including grasslands (pastures and páramo), shrublands, and forests, whether in rural or peri-urban settings [5]. This definition is functionally equivalent to the internationally used term 'wildfire', which encompasses all unplanned fires in natural or semi-natural vegetation. Throughout this manuscript, 'VCF' and 'wildfire' are used interchangeably, with 'VCF' preferred when referencing Colombian institutional frameworks and 'wildfire' when discussing international literature.

Globally, wildfire represents one of the most significant natural disturbances in terrestrial ecosystems. They alter vegetation structure, soil properties, carbon cycling, hydrological regimes, and biodiversity [7,8]. Beyond ecological impacts, wildfires impose substantial economic costs whose magnitude scales with fire severity, frequency, and the socioeconomic characteristics of affected territories [9]. In tropical and subtropical mountain ecosystems like the Colombian Andes, fire regimes are particularly complex because they operate at the intersection of climate drivers, topographic constraints, land-use change, and human management practices [10,11].

1.3. Climate Variability as a Driver of Fire Risk

The relationship between climate variability and wildfire risk is well-established in scientific literature. Fire regimes are sensitive to multi-scale climate dynamics, including interannual variability associated with ENSO, the Pacific Decadal Oscillation, and the Intertropical Convergence Zone (ITCZ) [12,13]. In Colombia, Armenteras-Pascual et al. [14] demonstrated that spatial fire patterns correlate strongly with climatic variables — particularly temperature anomalies and precipitation deficits — across the major biomes. More recently, Armenteras [15] documented significant shifts in burned area patterns in Colombia over the first two decades of the 21st century, attributing these changes in part to climate change-driven aridification. At the local scale, climate variability increases fire risk through a well-understood biophysical mechanism: reduced precipitation → soil moisture deficit → plant water stress → increased tissue flammability → elevated ignition probability and fire spread potential [16–18]. This chain of causation operates across vegetation types but is particularly pronounced in páramo ecosystems, where the dense, tussock-forming Espeletia grasslands and woody shrublands create a large, continuous fuel bed [19].

1.4. The Fire Weather Index as an Operational Tool

The Canadian Forest Fire Danger Rating System (CFFDRS) Fire Weather Index — hereafter FWI — is the most widely used operational fire danger index globally, having been validated across diverse biomes from boreal forests [20] to Mediterranean shrublands [21] and tropical mountain ecosystems [22]. The FWI integrates temperature, relative humidity, precipitation, and wind speed into a nested system of fuel moisture codes and fire behavior indices that track the drying and wetting of forest fuels across three depth layers [23]. Crucially, the FWI has been applied in several South

American contexts: Villers-Ruiz et al. [24] validated it in Mexican highland forests; Briones Monserrate [25] evaluated its performance in coastal Ecuador; and Alves et al. [26] applied it to transboundary fire risk in Iberia. These precedents underpin its adoption here for the high-altitude Colombian context. Several studies have successfully computed FWI from ERA5 reanalysis data — the same source used in this study — demonstrating that reanalysis products are viable substitutes for station-based inputs when ground observations are sparse, as is the case in Sumapaz [27,28]. Our key methodological innovation is the replacement of IDEAM's static vegetation susceptibility layer with the dynamic, meteorologically driven FWI within the threat equation, thereby transforming a baseline risk map into an operationally adaptive fire danger assessment tool.

1.5. Research Objectives and Scientific Questions

This study addresses three inter-related research questions:

RQ1: What is the spatiotemporal distribution of VCF events in Sumapaz (2001–2023), and which climatic and topographic factors best explain it?

RQ2: How does an integrated FWI-IDEAM risk framework perform in characterizing wildfire threat, vulnerability, and risk for this high-altitude páramo environment?

RQ3: What spatially explicit risk management strategies — grounded in the evidence from the risk assessment — are most viable for reducing VCF impacts in Sumapaz?

The overarching objective is to demonstrate that integrating dynamic meteorological fire danger modelling with a standardized vulnerability assessment can produce an operational risk management tool capable of anticipating fire events and informing targeted interventions — an approach with direct transferability to other biodiversity-rich, under-monitored mountain ecosystems in tropical Latin America.

2. Materials and Methods

2.1. Geographic and Administrative Context

Understanding the physical and administrative context of Sumapaz is essential to interpreting the wildfire risk patterns analysed in this study. Sumapaz is the 20th locality (district) of Bogotá, the Colombian capital, and is entirely rural. It is located at approximately 4°15′36″N, 74°10′42″W and extends across approximately 78,095 ha from the Eastern Cordillera into the Llanos and Magdalena piedmonts (Figure 1). It constitutes the world's largest contiguous high-altitude peatland-páramo complex and is designated as a national protected area under the Sumapaz National Natural Park. Administrative boundaries follow Agreement 9 of 1986: north — Usme and Ciudad Bolívar localities; south — Huila department; east — Meta department; west — the municipalities of Pasca, San Bernardo, Cabrera, and Venecia [6]. The locality is hydrologically structured around two major basin systems: the Blanco River basin (north, comprising the Tabaco, Santa Rosa, Chochal, and Gallo sub-basins) and the Sumapaz River basin (south, a tributary of the Magdalena), both nationally important for fresh water supply.

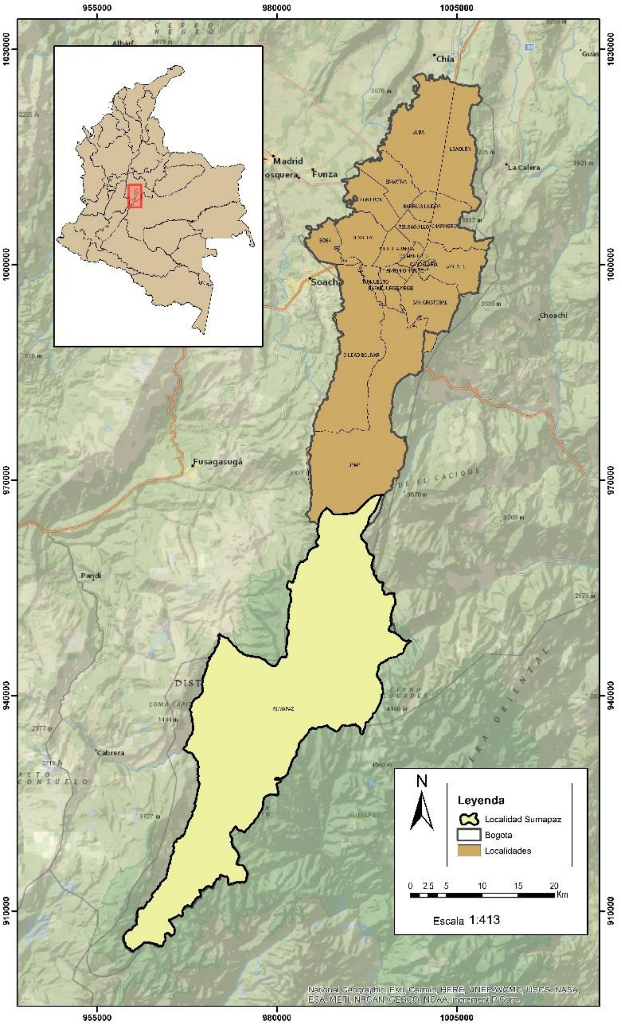

Figure 1. Geographic location of the Sumapaz locality (District 20 of Bogotá, Colombia), covering 78,095 ha in the Eastern Cordillera of the Andes. The locality encompasses the world's largest contiguous high-altitude páramo–peatland complex and constitutes the study area for this wildfire risk analysis. Inset (upper left) shows national context within Colombia. Administrative boundaries delimit the locality to the north by Usme and Ciudad Bolívar, to the south by Huila department, and to the east by Meta department. (Source: authors; cartographic base from IGAC and OpenStreetMap).

2.2. Topography and Ecological Complexity

The terrain is characterised by steep, highly dissected slopes with gradients ranging from <7% in narrow valley floors to >75% on escarpments in the southeast. Elevation spans 2,400 to over 4,100 m above sea level (m.a.s.l.), creating strong altitudinal gradients that generate distinct ecological zones. Between 3,500 and 3,900 m.a.s.l., the páramo ecosystem is dominated by frailejón tussock grassland (Espeletia grandiflora) with high biomass density. From 2,800 to 3,500 m.a.s.l., the sub-páramo transitions to shrublands dominated by Asteraceae, Ericaceae, Orchidaceae, and Melastomataceae families. Below 2,800 m.a.s.l., high-Andean and gallery forests (bosque ripario) occur along drainage corridors [24]. The locality encompasses 22 distinct natural ecosystems [4], representing 38.3% of Bogotá's total forested area. This high proportion, combined with the dense and continuously connected fuel bed, explains the locality's disproportionate share of fire occurrence.

2.3. Climatic Profile

Sumapaz exhibits two primary rainfall seasons driven by the biannual passage of the ITCZ: a main wet season from March–May (peak: April, ~375 mm/month) and a secondary wet season in

September–November (peak: October, ~289 mm/month). The main dry season (December–February) produces the lowest precipitation of the year (January minimum: ~143 mm/month) and coincides with reduced specific humidity (~7.81 kg/kg) and high solar radiation (February peak: ~15.4 MW/m²) — conditions that collectively maximize fuel desiccation and fire risk. Mean annual temperature is approximately 9.24°C, with limited seasonal variation but important diurnal fluctuations driven by altitude. Wind speeds range from 0.2 to >1.5 m/s; the predominant southeast airflow interacts with the Andean ridgeline to produce orographic acceleration and redistribution effects relevant to fire spread. The eastern slopes receive additional moisture from Amazonian and Orinoquian air masses, creating wetter microclimates, while the western slopes are influenced by dry, warm air from the Magdalena Valley [26,29]. The 2010 El Niño event produced the most extreme climatic anomaly in the study period: February 2010 had a maximum temperature of 11.17°C and the January 2010 Drought Code reached its series maximum, consistent with the highest fire activity year.

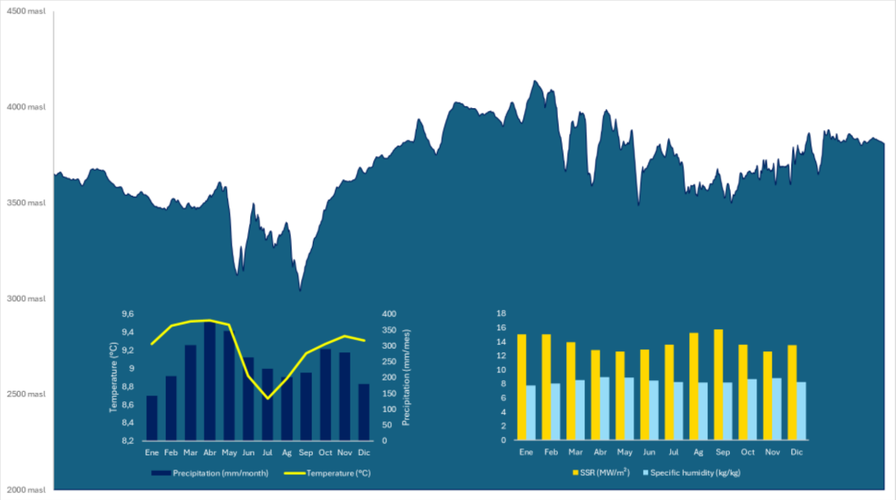

Figure 2. Multi-annual monthly average climate variables for the Sumapaz locality (2001–2023), derived from ERA5 reanalysis data: total precipitation (mm/month), mean air temperature (°C), downward solar radiation (MW/m²), and specific humidity (kg/kg). The bimodal rainfall regime driven by the Intertropical Convergence Zone (ITCZ) is evident, with wet seasons in March–May and September–November. The main dry season (December–February) — characterised by minimum precipitation (~143 mm in January), peak solar radiation (~15.4 MW/m² in February), and lowest specific humidity — coincides with peak wildfire occurrence in the locality. Left inset: wind rose showing dominant southeast airflow (2001–2023 mean). (Source: ERA5 reanalysis, ECMWF; figure by authors).

2.4. *Socioeconomic Landscape and Relevance to Fire Risk*

The human footprint in Sumapaz is concentrated in the northern sector, where approximately 4.25% of the land is under agroforestry use and a further 8.29% is classified as forestry. Potato cultivation is the dominant livelihood activity, supplemented by livestock farming and dairy production. Road infrastructure is severely limited: only 63.82 km of roads are passable under normal conditions, with a further 47.06 km of difficult-access tracks and 18.25 km of high-risk roads in steep terrain (Figure B3, supplementary material). This accessibility deficit critically constrains emergency response capacity. Agricultural burning is a well-documented ignition source in Colombian Andean localities [10,30], making this predominantly farming area a priority target for ignition management. The coincidence of economic activity, limited infrastructure, and abundant fuel biomass in the northern zone creates a socio-ecological context highly predisposed to wildfire occurrence and limited suppression capacity.

2.5. Data Sources and Processing

The analysis integrates five categories of data covering the period 2001–2023 (Table 1). All spatial datasets were projected to the MAGNA-SIRGAS coordinate system (EPSG:3116), clipped to the Sumapaz locality boundary, and resampled to a common spatial resolution of 500 m to enable layer integration in ArcGIS Pro 3.1.

Table 1. Input datasets. ERA5 spatial resolution (~31 km) is a known limitation in complex terrain; implications are discussed in Section 6.4.

Category	**Variable**	**Source**	**Spatial Resolution**	**Temporal Resolution**	**Reference**
Fires	Active fire detections	MODIS FIRMS (MCD14DL, Collection 6.1)	1 km (nadir)	Daily, 2001–2023	[31]
Climate	Temperature (2 m)	ERA5 (Copernicus/ECMWF)	0.25° (~31 km)	Monthly means, 2001–2023	[32]
Climate	Precipitation	ERA5	0.25° (~31 km)	Monthly means, 2001–2023	[32]
Climate	Specific humidity	ERA5	0.25° (~31 km)	Monthly means, 2001–2023	[32]
Climate	Solar radiation (SSR)	ERA5	0.25° (~31 km)	Monthly means, 2001–2023	[32]
Climate	Wind speed/direction (10 m)	ERA5	0.25° (~31 km)	Monthly means, 2001–2023	[32]
Climate	Dry-bulb temperature	ERA5	0.25° (~31 km)	Monthly means, 2001–2023	[32]
Socioeconomic	Population density	DANE (census)	Veredal polygon	2001–2023	[33]
Socioeconomic	Land use / Protected areas	IGAC	1:25,000 polygon	2023 snapshot	[34]
Socioeconomic	Road / energy infrastructure	IGAC	1:25,000 line/point	2023 snapshot	[34]
Vegetation	Forest cover / land cover	MapBiomas Colombia (MODIS)	30 m (annual)	1990–2023	[35]

A critical limitation of the MODIS active-fire product is its well-documented tendency to underestimate fire counts in areas of dense smoke, closed-canopy forest, and small fires (<0.1 ha)

[36,37]. Studies of Australian megafires demonstrated that MODIS hotspots captured considerably less burned area than ground-based assessments [36]. For Sumapaz, this means the 128 recorded fire events likely represent a conservative estimate, particularly for small fires in dense páramo canopy. Results should therefore be interpreted as characterizing the spatial pattern of fires rather than providing a definitive count. ERA5 data, while providing the best available consistent climate record over 23 years, has a coarse resolution (~31 km) that cannot resolve sub-grid topographic effects (valley microclimates, orographic precipitation shadows) critical in complex mountain terrain. Downscaling to the locality's local stations was not performed due to the paucity of operational AWS within Sumapaz; this limitation is acknowledged in the FWI uncertainty discussion (Section 6.4).

2.6. Methodology

The methodology integrates three analytical tracks (Figure 3): (A) spatial and temporal fire occurrence analysis; (B) meteorological fire danger estimation through the FWI system; and (C) socioeconomic and ecological vulnerability scoring following the IDEAM protocol. These are combined into a composite risk index and classified into five risk zones. The central innovation is the substitution of IDEAM's static vegetation susceptibility parameter in the threat equation with the dynamic FWI, converting a once-in-a-generation mapping exercise into a monthly-updatable operational assessment.

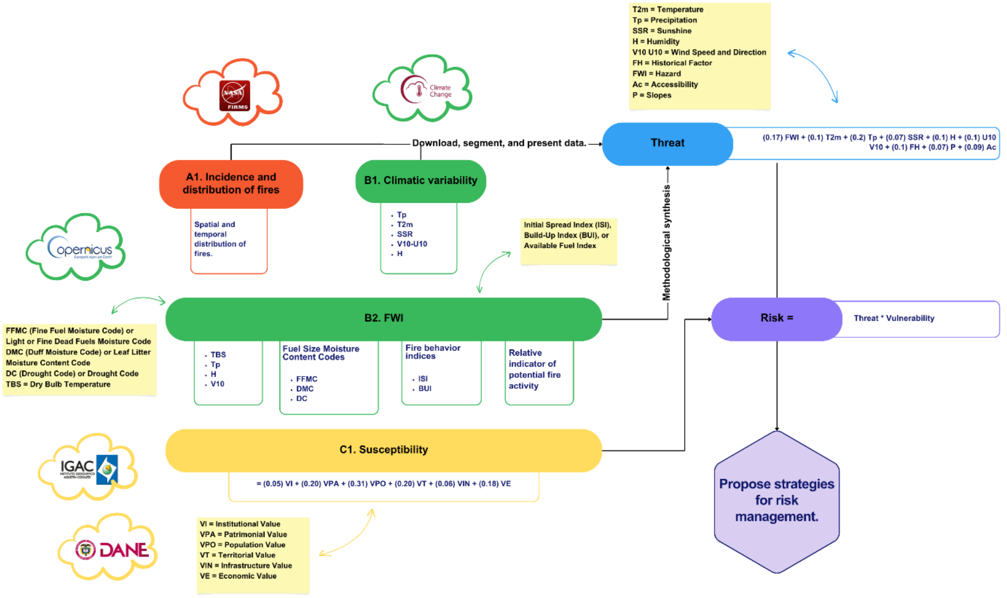

Figure 3. Integrated research methodology framework applied in this study. Three parallel analytical tracks are executed simultaneously: (1) spatiotemporal fire occurrence analysis using MODIS FIRMS active-fire detections and Kernel Density Estimation; (2) Fire Weather Index (FWI) computation from ERA5 reanalysis inputs for each month of the 2001–2023 period; and (3) vulnerability assessment using population, infrastructure, and institutional exposure indicators. All three outputs are integrated through the IDEAM multi-component risk equation to generate composite Threat, Vulnerability, and Risk classification maps. The resulting risk zoning directly informs the three-pillar risk management strategy developed in Section 7. (Source: authors).

2.7. Spatial and Temporal Fire Occurrence Analysis

MODIS FIRMS active-fire detections (Collection 6.1, MCD14DL) for the Sumapaz boundary were downloaded for January 2001 – December 2023. Each detection point carries a confidence level (low/nominal/high); only detections with ≥50% confidence were retained to minimise false positives, following standard practice [37,38]. Monthly and annual counts were aggregated to produce the fire time series. Spatial clustering was quantified using Kernel Density Estimation (KDE) with an adaptive bandwidth selected by Silverman's rule-of-thumb [39], identifying the four principal fire epicenters within the locality. Linear regression was applied to annual fire counts to test for trends over the study period. Forest cover change (1990–2022) was derived from the MapBiomas annual land cover maps classified from MODIS imagery at 30 m, providing a proxy time series for fuel availability and land-use change [35].

2.8. FWI Computation from ERA5 Reanalysis

The FWI system was implemented in Python following the original Van Wagner and Pickett [23] equations. Monthly ERA5 variables (temperature at 2 m, specific humidity converted to relative humidity, precipitation, and 10-m wind speed) were bilinearly interpolated to the Sumapaz centroid and to a 0.25° grid covering the locality extent. The FWI calculation proceeds through three successive code layers (Figure B1, supplementary material):

Fuel Moisture Codes: Three codes track moisture in progressively deeper organic soil layers. The Fine Fuel Moisture Code (FFMC) models the moisture content of fine surface litter — the primary indicator of ignition probability — and responds rapidly to temperature, humidity, and precipitation [40]. Values approach 100 under extreme drying. The Duff Moisture Code (DMC) represents intermediate-depth, loosely compacted organic matter; its drying rate is slower (modelled with a half-drying time of ~12 days). The Drought Code (DC) tracks deep, compact organic layers, responding to cumulative seasonal drought with a half-drying time of ~52 days; high DC values indicate deep, persistent combustion potential and are particularly relevant for identifying years of extreme fire danger [40,41].

Fire Behavior Indices: The Initial Spread Index (ISI) combines wind speed and the FFMC to estimate the rate of fire spread on open, flat terrain, independent of fuel load. The Build-Up Index (BUI) combines DMC and DC to quantify the total available fuel for combustion, including heavy fuels that sustain burning. The final FWI is a composite of ISI and BUI, categorized following AEMET [42] into five danger classes: Low (0–5.9), Moderate (6–14.9), High (15–27.9), Very High (28–45.9), and Extreme (>46) (Table B1, supplementary material). These thresholds were validated for the Sumapaz context by confirming that high FWI months temporally align with documented fire events in the FIRMS record.

Comparison with existing studies: Briones Monserrate [25] applied the FWI at a similar altitude (500–1,500 m.a.s.l.) in coastal Ecuador and found that ERA5-derived inputs produced FWI values consistent with fire occurrence records, supporting the approach here. Alves et al. [26] and ECMWF [43] have demonstrated FWI skill in complex terrain using reanalysis data, though both note that coarse resolution underestimates peak danger in topographic constrictions — a caveat directly applicable to Sumapaz.

2.9. Threat (AM) Assessment: Integrating FWI with Climatological and Topographic Factors

Consistent with the IDEAM (2011) protocol [5] — the legally mandated framework for wildfire risk zoning in Colombia — the Threat (AM) was calculated as a weighted linear combination of the dynamic FWI and eight additional factors that are known drivers of fire ignition and spread (Equation 1). The FWI replaces the static susceptibility map originally prescribed by IDEAM, making threat time-varying and responsive to climatic conditions.

$$\begin{aligned} AM = {} & (0.17)\cdot FWI + (0.10)\cdot T2m + (0.20)\cdot Tp + (0.07)\cdot SSR + (0.10)\cdot H \\ & + (0.10)\cdot (U10,V10) + (0.10)\cdot FH + (0.07)\cdot P + (0.09)\cdot Ac \end{aligned} \tag{1}$$

Where: AM = Threat score; FWI = Fire Weather Index; T2m = air temperature (2 m); Tp = precipitation; SSR = solar radiation (sunshine); H = specific humidity; U10,V10 = wind speed and direction; FH = historical fire frequency factor; P = terrain slope; Ac = accessibility (inverse road density).

Weighting rationale (Table 2):

Table 2. Weighting justification for Threat Equation 1. Weights were adopted from IDEAM [5] for climatological variables and infrastructure, with FWI substituted for the static susceptibility layer; precipitation received the highest non-FWI weight based on its strongest empirical correlation with fire occurrence observed in this dataset.

Variable	Weight	Justification	Source
FWI	0.17	Primary meteorological fire danger indicator; largest single weight as it integrates multiple climate variables	[23,42]
Precipitation (Tp)	0.20	Greatest direct control on fuel moisture; second-highest weight per correlation analysis (r = −0.71 with FWI)	This study
Temperature (T2m)	0.10	Indirect driver through evapotranspiration	[14,17]
Wind (U10,V10)	0.10	Determines spread rate once ignited	[41]
Humidity (H)	0.10	Direct fuel moisture control; covariate with precipitation	[16]
Historical factor (FH)	0.10	Fire recurrence at same location increases probability	[5]
Accessibility (Ac)	0.09	Influences both ignition (human access) and suppression capacity	[5,30]
Solar radiation (SSR)	0.07	Indirect driver; correlates with temperature (r = 0.23)	This study

Slope (P)	0.07	Affects spread rate and suppression difficulty	[5,41]

All input variables were normalized to a 1–5 scale using quantile classification (20th, 40th, 60th, 80th, and 100th percentiles of the spatial distribution within the locality) prior to summation, ensuring dimensional consistency. Scores of 1 = Very Low and 5 = Very High threat contribution.

2.9.1. Vulnerability (VUL) Assessment

Vulnerability was assessed following Equation 2, which combines six socioeconomic and ecological exposure dimensions originally defined by IDEAM [5] and applied in comparable Colombian fire risk studies [44]:

$$VUL = (0.05)\cdot VI + (0.20)\cdot VPA + (0.31)\cdot VPO + (0.20)\cdot VT + (0.06)\cdot VIN + (0.18)\cdot VE \qquad (2)$$

Where: VI = Institutional vulnerability (capacity of emergency response bodies); VPA = Patrimonial vulnerability (cultural heritage and natural protected areas); VPO = Population vulnerability (population density and proximity to fire zones, highest weight reflecting the primary objective of protecting human life); VT = Territorial vulnerability (land use, slope classes, ecosystem types); VIN = Infrastructure vulnerability (roads, electrical, communication); VE = Economic vulnerability (agricultural and forestry economic activity exposed).

VPO carries the highest weight (0.31) in Equation 2 because the primary objective of DRM is protection of human life and livelihoods. VPA (0.20) and VT (0.20) receive equal secondary weight reflecting the importance of natural heritage (páramo protected status) and land-use exposure. VE (0.18) reflects the economic dependency on agroforestry. VI (0.05) and VIN (0.06) receive lowest weights as they represent capacity factors rather than exposure, consistent with the original IDEAM formulation [5] and validated in Torres [44] for a comparable Bogotá locality. Each component was scored 1–5 using spatial data from DANE, IGAC, and the local risk plan [6,33,34].

2.9.2. Risk Integration and Zoning

The composite Risk index was calculated as the product of Threat and Vulnerability (Equation 3), consistent with the multiplicative risk formulation standard in quantitative natural hazard literature [45]:

$$\text{Risk} = \text{Threat (AM)} \times \text{Vulnerability (VUL)} \qquad (3)$$

The multiplicative form is preferred over an additive approach because it ensures that areas with very high vulnerability but no threat (or vice versa) do not yield artificially elevated risk scores. Risk scores were classified into five categories (Very Low, Low, Moderate, High, Very High) using Jenks natural breaks optimisation applied to the frequency distribution of the spatial grid, following the IDEAM classification protocol [5] (Table 3). This classification was applied to the entire Sumapaz grid and is presented in the final zoning maps (Figure 10).

Table 3. Risk category classification (source: adapted from IDEAM, 2011 [5]).

Score Class	Risk Category
1	Very Low
2	Low
3	Moderate
4	High
5	Very High

2.9.3. Risk Management Strategy Development

The management strategies were developed through a structured process: (1) the composite risk map was used to identify priority intervention zones; (2) the causal factors identified in the threat and vulnerability analyses were translated into actionable intervention types; (3) feasibility of each action was scored using a multi-criteria assessment (Table 4) by a panel of four evaluators with expertise in fire ecology, territorial planning, and environmental engineering; and (4) strategies were aligned with the three pillars of Colombia's National Disaster Risk Management Plan (PNGRD 2015–2030: Law 1523/2012) [46,47].

Table 4. Multi-criteria scoring matrix for management action feasibility assessment.

Score	**Environmental Viability**	**Technical Feasibility**	**Economic Viability**	**Effectiveness**
1	Very poor	Very difficult	Very costly	Very low
2	Poor	Difficult	Costly	Low
3	Moderate	Moderate	Moderate	Moderate
4	Good	Feasible	Affordable	High
5	Very good	Very feasible	Very affordable	Very high

3. Results

3.1. Spatiotemporal Pattern of VCF Occurrence

Sumapaz accounted for 64.9% of all FIRMS-detected VCF events in Bogotá between 2001 and 2023 (128 events; 815.43 ha burned), far exceeding Fontibón (11.6%) and Usme (10.6%) (Figure 4a). Sixty-three percent of the locality's vegetation cover surface has experienced at least one fire over the study period. Peak fire years were 2001, 2003–2005, and 2010; these correspond to La Niña–El Niño transition periods and the strong 2009/10 El Niño event documented by IDEAM [48]. Fire occurrence shows a marked seasonality: 78% of all detected events occur between December and March (the main dry season), with February being the single most active month (Annex A, Figure A1 and A2).

The KDE analysis identifies four principal hot-spot epicenters in the locality (Figure 4b). The most intense cluster (hard hotspot category) is located in the northern zone near the Blanco River basin, coinciding with: (i) the highest density of agroforestry and forestry land use; (ii) the main population concentration; and (iii) the documented distribution of the invasive thorny broom (Ulex europaeus). A second hard hotspot occurs on the eastern escarpment, corresponding to the steepest terrain (>50% slopes) with high solar radiation exposure. Two medium-intensity epicenters occur in the central zone, where agricultural burning practices have been linked to ignition [6,30]. The persistence of these epicenters across the 23-year record suggests location-specific conditions — not random climate events — as the primary determinant of fire ignition sites.

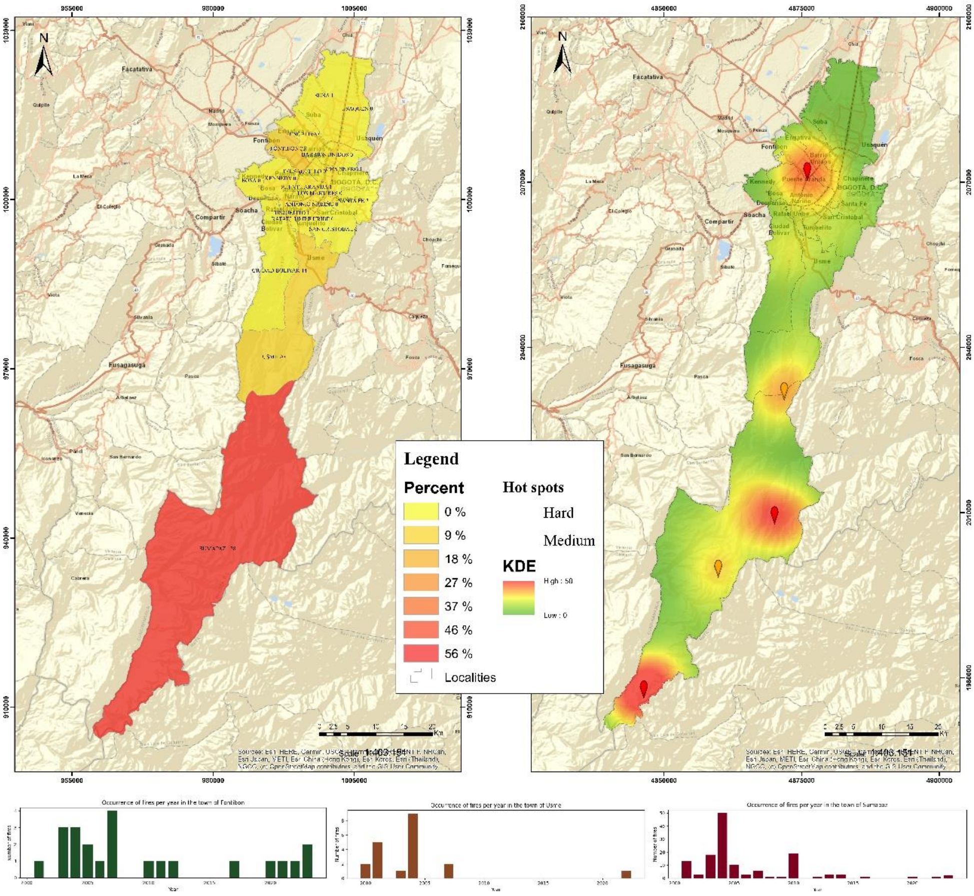

Figure 4. Spatiotemporal analysis of Vegetation Cover Fire (VCF) occurrence in Bogotá (2001–2023) based on MODIS FIRMS active-fire detections. (a) Annual VCF event counts by locality: Sumapaz accounts for 64.9% of all 197 events recorded across Bogotá's 20 localities, totalling 128 fires covering approximately 815.43 ha; Fontibón (11.6%) and Usme (10.6%) rank second and third. (b) Kernel Density Estimation (KDE) hot-spot map for Sumapaz showing four fire epicenters: two high-intensity clusters in the northern agroforestry zone (Nazareth and San Juan sectors) and two medium-intensity zones near the sector border with Usme and Ciudad Bolívar. Peak fire years (2001, 2003–2005, 2010) correspond to El Niño–Southern Oscillation (ENSO) warm phases. Temporal bar chart insets show annual fire counts by locality. (Source: MODIS FIRMS, NASA; spatial analysis by authors).

3.2. Land Use, Forest Cover Change, and the Invasive Species Factor

Land use analysis (Figure 5) shows that fire epicenters overlap predominantly with agroforestry (4.25% of locality area, 6,899 ha) and soil conservation zones (34.42%, 55,852 ha) — areas that combine abundant fuel biomass with periodic human disturbance. Forest cover analysis (Figure 6, Table A2) shows a slight positive trend from 1990 (37.95% of locality) to 2015 (38.61%), followed by a decline to 37.58% in 2022, representing a net loss of ~0.95% of vegetated cover over the study period. This 2020–2022 decline is temporally associated with documented land-use change linked to agricultural frontier expansion in the northern sector.

A specific and growing concern is the northward spread of thorny broom (Ulex europaeus), an invasive shrub native to Western Europe. This species is highly pyrogenic due to its accumulation of volatile oils, dense dry biomass, and ability to resprout prolifically after fire — creating a positive fire feedback cycle [49]. Current mapping estimates approximately 2 ha of established U. europaeus within Sumapaz (0.32% of Bogotá's total U. europaeus coverage), with a modelled potential expansion area of ~9 ha based on seed dispersal modelling (wind transport and endozoochory), representing a 467% increase (Figure D1, supplementary material). The primary expansion direction coincides with the most active northern fire epicenter, where the existing shrub patch is likely an active ignition amplifier for adjacent native vegetation.

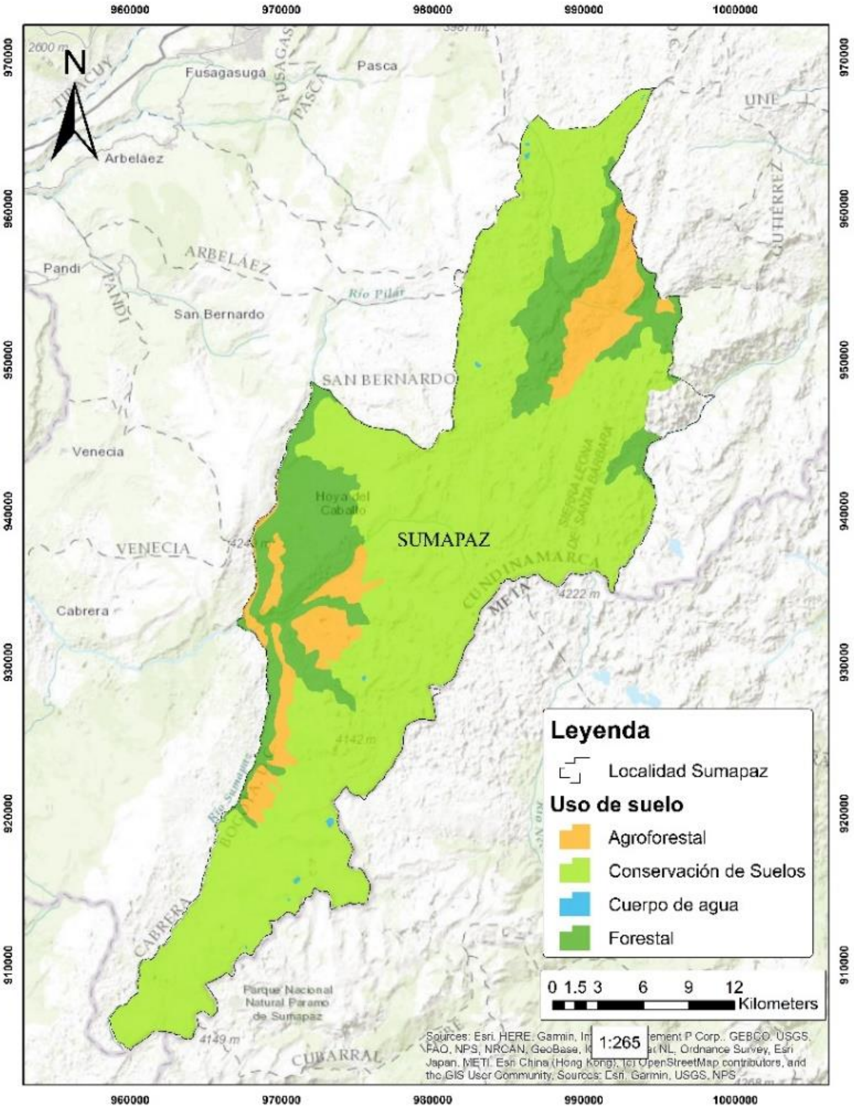

Figure 5. Land use classification map of the Sumapaz locality (based on IGAC cartography, 2020). The dominant land use categories are soil conservation (Conservación de Suelos; 34.42% of total area, 55,852 ha), agroforestry (Agroforestal; 4.25%, 6,899 ha), and forestry (Forestal). Fire epicenters identified through KDE analysis (reproduced from Figure 4b) overlap predominantly with the agroforestry and soil conservation zones in the northern sector — confirming that land use is a primary spatial mediator of fire ignition risk. The presence of Ulex europaeus (thorny broom) is concentrated in transitional zones between agroforestry and conservation areas. Spanish legend translated: Agroforestal = Agroforestry; Conservación de Suelos = Soil Conservation; Forestal = Forestry; Área Urbana = Urban Area; Cuerpo de Agua = Water Body. (Source: IGAC; spatial overlay by authors).

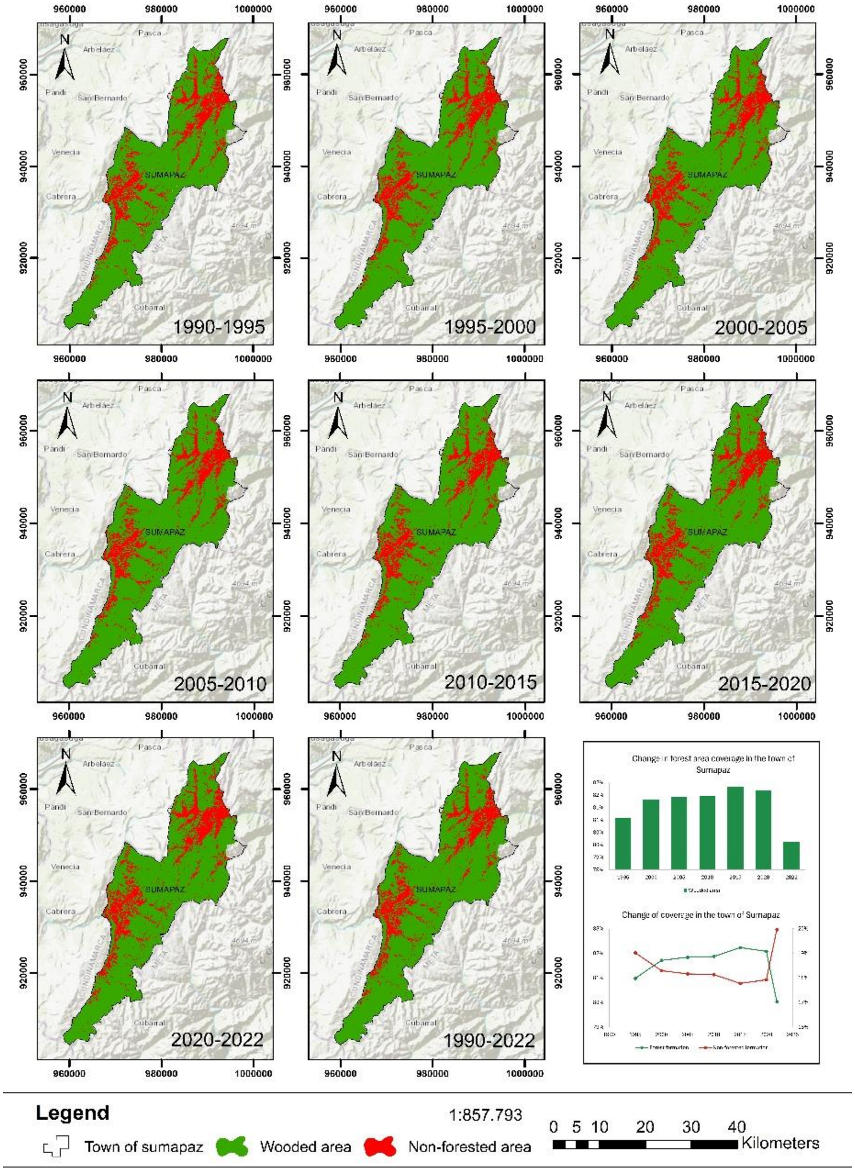

Figure 6. Temporal dynamics of forest cover change in Sumapaz (1990–2022), derived from MapBiomas Colombia land-cover classification at 30 m spatial resolution. Sequential maps show forest cover (green) and non-forest area (red) at five-year intervals, capturing a net gain phase (1990–2015: from 37.95% to 38.61% of locality area) followed by a decline to 37.58% by 2022 — a net loss of approximately 0.95% of vegetated cover (~742 ha) over the full period. The bottom-right panel quantifies the change trajectory as an annual time series. The 2020–2022 acceleration in non-forest area is spatially coincident with agricultural frontier expansion in the northern sector and corresponds to a period of elevated fire frequency. Forest cover loss reduces the moisture retention capacity of the páramo, increasing fuel desiccation rates and wildfire susceptibility. (Source: MapBiomas Colombia v.3; figure by authors).

3.3. Climatic Dynamics and FWI Analysis

The multi-annual climate time series (Figure 7) confirms the bimodal precipitation regime and highlights the December–February dry season as the critical fire window. The correlation matrix (Figure 8a) reveals that, among the five climatic variables considered: (i) precipitation (Tp) has the strongest negative correlation with fire occurrence (Pearson $r = -0.71$; $p < 0.01$) and with FWI ($r = -0.43$); (ii) specific humidity (H) also correlates negatively with FWI ($r = -0.45$); (iii) temperature (T2m) and solar radiation (SSR) correlate positively with FWI ($r = +0.32$ and $+0.23$, respectively); and (iv) all four variables together explain approximately 63% of the FWI variance ($R^2 = 0.63$, multiple regression, p < 0.001). These results confirm the expected climatological relationships and are consistent with findings from Armenteras-Pascual et al. [14] for Colombian biomes broadly. Importantly, no single variable is individually sufficient to predict fire occurrence — their synergistic interaction under specific conditions (low H, low Tp, high T2m, high SSR simultaneously) creates the conditions for extreme fire danger. This underscores the value of the composite FWI over any single-variable approach.

The inter-correlation matrix for FWI components (Figure 8b) shows strong positive associations among all sub-indices (r = 0.49–0.96), confirming internal consistency. The DC–BUI correlation (r = 0.95) reflects the dominant role of cumulative seasonal drought in determining total fuel availability, which is particularly relevant in Sumapaz's deeply organic soils.

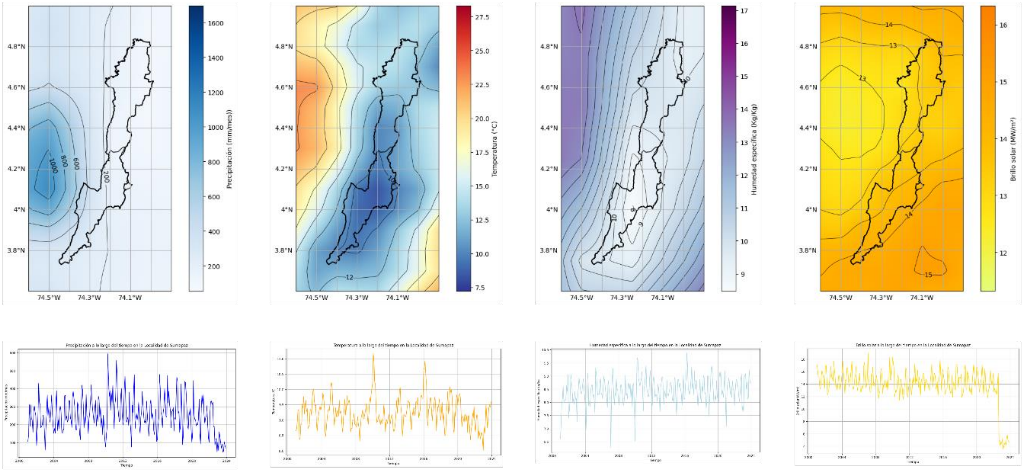

Figure 7. Monthly multi-annual averages of key climatic variables for Sumapaz (2001–2023) from ERA5 reanalysis, illustrating the seasonal climate regime that drives wildfire risk. Precipitation (blue line, mm/month) shows a bimodal pattern with a minimum in January (~143 mm); temperature (orange line, °C) shows a mean of ~9.24°C; downward solar radiation (yellow bars, MW/m²) peaks in February (~15.4 MW/m²); specific humidity (teal line, kg/kg) reaches its minimum during the December–March dry season (~7.81 kg/kg). The convergence of low precipitation, high radiation, and low humidity during December–March constitutes the primary fire weather window. Labelled markers indicate anomalous values during the 2010 El Niño event — the year of peak fire activity in the study period (19 events) — and the 2023 dry season. These extremes validate the FWI as a sensitive detector of elevated fire danger conditions. (Source: ERA5 reanalysis, ECMWF; figure by authors).

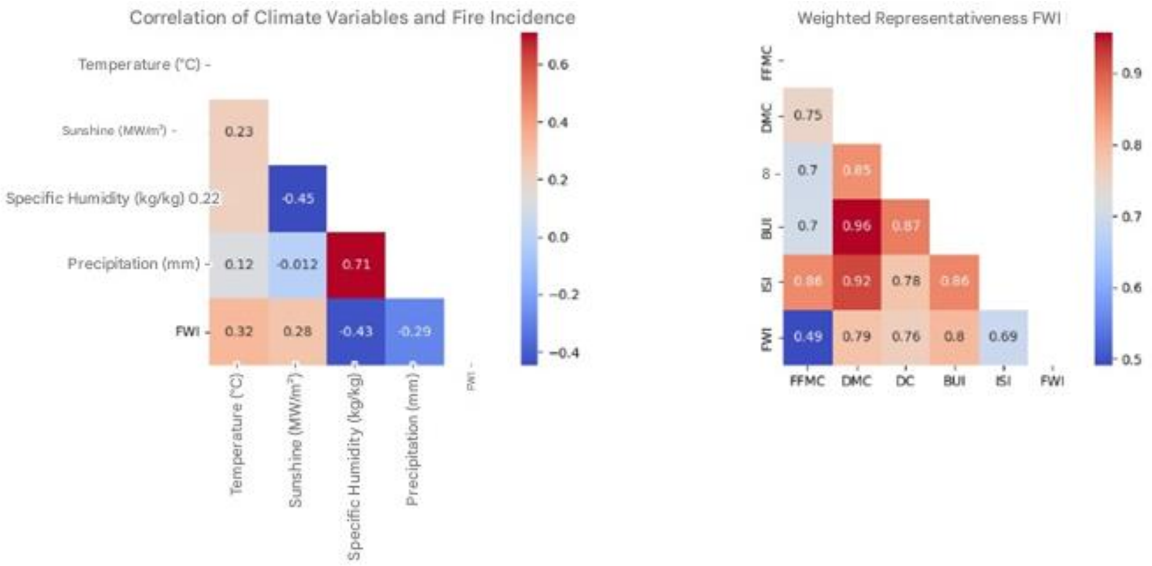

Figure 8. Statistical relationships between climatic drivers and fire danger indices for Sumapaz (2001–2023). (a) Pearson correlation matrix between monthly climatic variables (precipitation, temperature, solar radiation, specific humidity, wind speed) and the composite FWI score: precipitation shows the strongest inverse correlation ($r = -0.71$), followed by specific humidity ($r = -0.45$), while temperature ($r = +0.32$) and solar radiation ($r = +0.23$) show moderate positive associations. Together these variables explain 63% of FWI variance ($R^2 = 0.63$, multiple regression, $p < 0.001$). (b) Inter-correlation matrix of FWI sub-indices: Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), Drought Code (DC), Buildup Index (BUI), Initial Spread Index (ISI), and composite FWI. High internal correlations confirm the coherent dynamic behaviour of the FWI system. Colour scale: red = strong positive correlation; blue = strong negative correlation; white = near-zero correlation. (Source: ERA5 inputs; Pearson correlations computed by authors).

3.4. FWI Time-Series Results and the 2010 Case Study

The long-term mean FWI for Sumapaz over 2001–2023 is 0.78, classified as Low danger (threshold 0–5.9). This low average reflects the fact that the wet season occupies ~8–9 months and keeps fuel moisture above critical thresholds for most of the year. The critical fire window is narrow but intense. The year 2010 provides the most compelling validation of the FWI model. This year recorded the highest number of large fire events in the study period (19 active FIRMS detections). The FWI time series (Figure 9) shows all sub-indices reaching their study-period maxima during January–February 2010: FFMC = 85.86 (extreme ignition probability for surface litter), DC = 237.18 (exceptional deep-layer drought), BUI = 50.3 (maximum available fuel load), ISI = 5.53 (elevated fire spread rate), and the overall FWI peaked at 13.7 in February 2010 (Moderate-to-High danger class: threshold 6–14.9). The spatial FWI map for January 2010 shows the highest values concentrated in the northern and northeastern zones — precisely matching the FIRMS hotspot epicenters identified in Section 5.1. This spatial and temporal congruence between modelled fire danger and observed fire events transforms the FWI system from a theoretical construct into a validated operational tool for Sumapaz. The alignment is consistent with FWI validation studies in comparable South American contexts [25,26].

For the broader 2001–2023 period, the FWI categorization correctly identifies the peak fire months (January–February) as the only months with frequent transitions above the Low danger threshold, with occasional Moderate and High values in the dry season. Months within the wet season (April–June, October–November) consistently produce Low or near-zero FWI values, consistent with negligible fire activity.

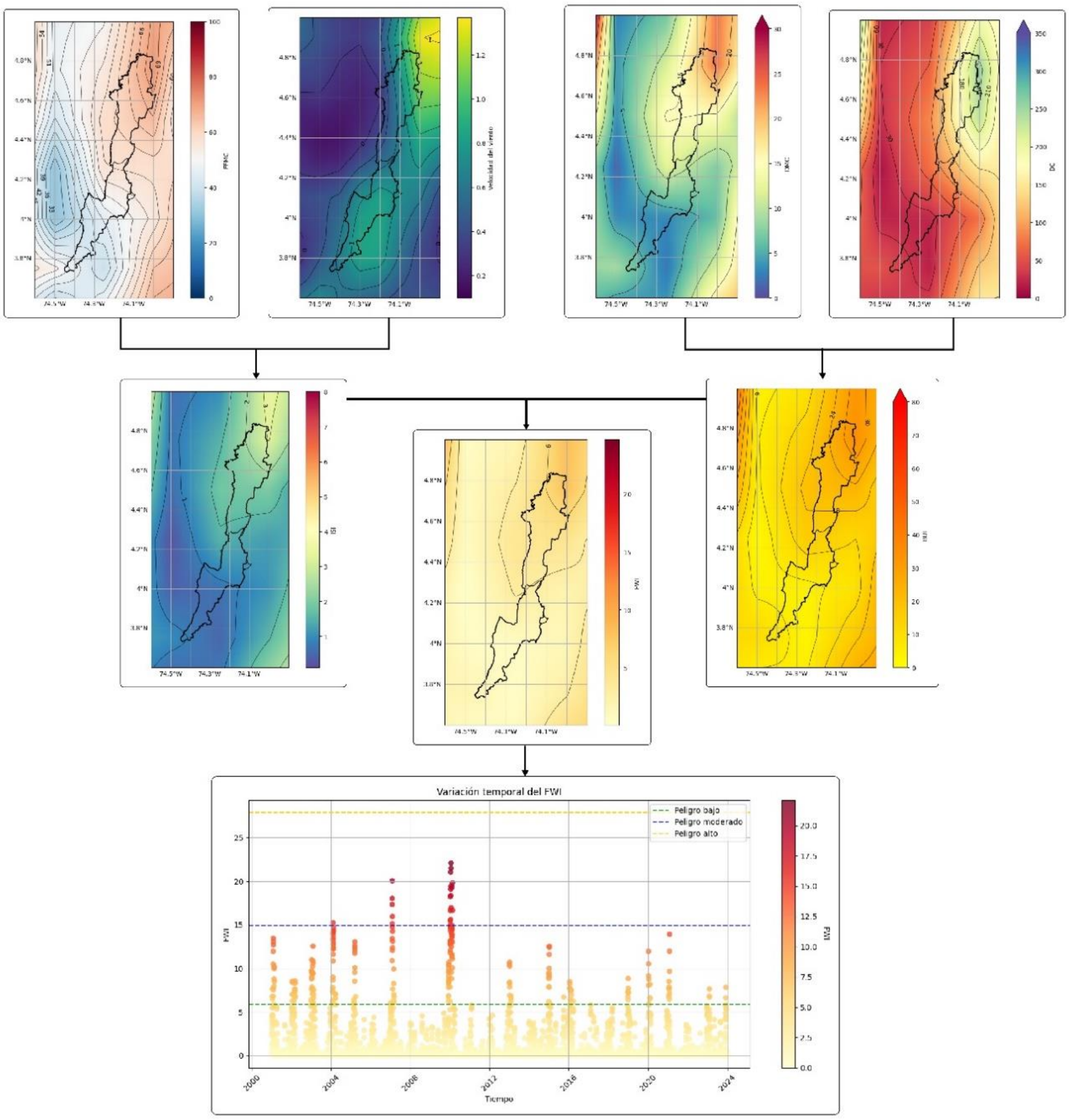

Figure 9. Fire Weather Index (FWI) system results for the Sumapaz locality (2001–2023). Top row: spatial distribution maps of FWI sub-indices for January 2010 — the month of peak fire danger in the study period — showing Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), Drought Code (DC), Buildup Index (BUI), Initial Spread Index (ISI), and composite FWI across the locality. The northern sector consistently shows higher danger class values, corresponding spatially to the fire epicenters identified in Figure 4b. Bottom panel: full monthly FWI time series (2001–2023) with danger class thresholds shown as horizontal dashed lines (Low, Moderate, High, Very High). The 2010 peak (FWI = 13.7 in February) is clearly the highest in the series and is validated by the highest annual fire count (19 events recorded by MODIS FIRMS). Mean FWI across the study period = 0.78 (Low danger class). (Source: FWI computed from ERA5 reanalysis using Canadian CFFDRS algorithms; figure by authors).

3.5. Risk Zoning: Threat, Vulnerability, and Integrated Risk

The integrated threat, vulnerability, and risk maps are presented in Figure 10. Table 5 provides quantitative area statistics for each classification level.

Table 5. Quantitative area statistics for threat, vulnerability, and integrated risk classification. Threat is dominated by moderate levels; risk reflects the interaction of moderate threat with heterogeneous vulnerability.

doi:10.20944/preprints202603.1832.v1

Category	Threat (% area)	Vulnerability (% area)	Risk (% area)
Very Low	0.02	1.19	1.12
Low	5.92	27.30	49.09
Moderate	92.06	67.47	43.34
High	2.01	2.69	2.93
Very High	0.00	1.06	0.77

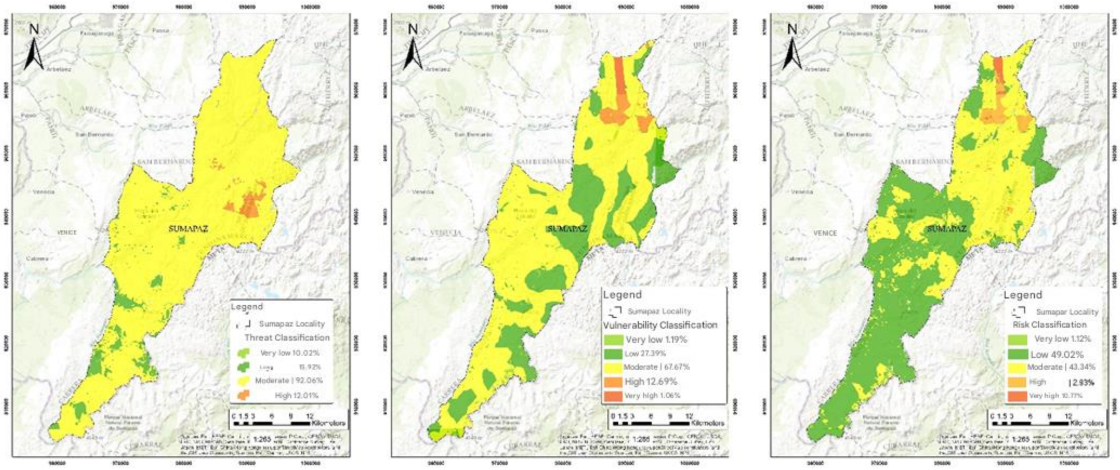

Figure 10. Wildfire risk zoning maps for the Sumapaz locality, produced through the integrated IDEAM multi-component framework applied in this study. (a) VCF Threat classification: 92.06% of the locality area falls under Moderate threat, driven by the combination of 12–25% terrain slopes and high biomass fuel loads; 3.97% Very High/High threat concentrated in the northeastern escarpments and U. europaeus invasion zone. (b) VCF Vulnerability classification: 67.47% Moderate vulnerability, concentrated in the northern populated sector; 3.33% High/Very High vulnerability associated with proximity to rural settlements and key road infrastructure (147 road elements mapped, of which 27 are classified as high-risk). (c) Integrated VCF Risk map (composite of Threat × Vulnerability): 49.09% Low risk (central-south páramo core), 43.34% Moderate risk (northern agroforestry and transition zones), and 3.70% High/Very High risk (~2,889 ha) in the northeastern escarpments, U. europaeus invasion front, and densely settled northern sub-sectors. The spatial pattern confirms that risk is governed by the coincidence of topographic, ecological, and social exposure factors, not by climate alone. (Source: authors; data inputs from ERA5, IGAC, DANE, MODIS FIRMS, and field surveys).

Threat (Figure 10a): The overwhelming dominance of Moderate threat (92.06%) reflects the pervasive combination of 12–25% slopes and high vegetative vigor across the locality. High threat areas (2.01%) are concentrated in the southeastern escarpments with slopes of 25–75%, receiving high solar radiation due to northward aspect, which accelerates fuel drying. The Very Low and Low categories (0.02% and 5.92%) correspond to valley bottoms and southern wetland areas where soil moisture is consistently high.

Vulnerability (Figure 10b): Moderate vulnerability dominates (67.47%), reflecting the widespread distribution of flammable native vegetation (herbazal: 902 ha; pastos limpios: 537 ha; bosque de galería: 193 ha; arbustales: 159 ha — all in the High or Very High ecosystem vulnerability category; Tables C1 and C2, supplementary material). The northern sector shows higher vulnerability due to the concentration of population (VPO), economic activity (VE: agroforestry), and supporting infrastructure (VIN). The population distribution is overall very sparse (Very Low and Low: 28.49% combined) due to the high-altitude conditions limiting settlement.

Integrated Risk (Figure 10c): The spatial pattern of risk reflects the interaction between moderate threat and heterogeneous vulnerability. Low risk (49.09%) dominates the central-south zone where dense, well-hydrated high-Andean and páramo vegetation has minimal exposure to human activity. Moderate risk (43.34%) covers the northern and central zones, where moderate threat coincides with agricultural vulnerability. High and Very High risk areas (3.70% combined, ~2,889 ha absolute) are geographically discrete: they correspond to north-eastern slopes combining terrain gradients >25%, proximity to U. europaeus invasion, concentrated human settlement, and the highest FWI values. This small but critical footprint should be the priority focus for active management interventions. The road network risk assessment identifies 147 total road elements, of which 75 (47.06 km) are in the Moderate risk zone and 27 (18.25 km) in the High risk zone — the latter with severely limited suppression access capacity.

4. Discussion

4.1. Drivers of Fire Distribution: Beyond Single-Variable Explanations

The finding that VCF events in Sumapaz are concentrated in a small number of persistent epicenters — rather than being randomly distributed — is consistent with the conceptual framework of fire as a landscape-level process mediated by the coincidence of fuel, ignition sources, and weather [7,10]. Contrary to simplistic attributions of fire to climate variability alone, our results confirm that no single climatic variable is an adequate predictor: precipitation has the strongest correlation with fire danger ($r = -0.71$ with FWI), but topography (slope, aspect), land use (agricultural burning), and biological factors (U. europaeus fuel bed quality) are necessary co-drivers that localise fire in space regardless of regional climate state. This finding aligns with Amaya and Armenteras [50] for Cundinamarca broadly, who demonstrated that fire patterns in Colombian Andean landscapes are governed by the synergistic interaction of climate and landscape factors, not by any single variable.

The role of the invasive thorny broom (U. europaeus) as a fire amplifier warrants particular attention. As documented by Martínez [51] and Barrera & Rojas [49], U. europaeus creates a positive fire-invasion feedback loop: fire facilitates seedbank germination and reduces competition from native species; in turn, the growing U. europaeus stand increases fuel flammability and load, raising fire severity in subsequent events. Our seed dispersal model suggests a potential 467% expansion from current 2 ha to ~9 ha, primarily tracking the dominant southeast wind direction towards the northern fire epicenter. Early control is therefore not merely an ecological priority but an urgent fire risk management imperative.

4.2. Performance of the Integrated FWI–IDEAM Framework

The primary methodological contribution of this study is the replacement of IDEAM's static vegetation susceptibility parameter with the dynamic FWI. The validation with the 2010 El Niño case study demonstrates that this substitution produces a meaningful and interpretable improvement in threat characterisation: the FWI correctly flags January–February 2010 as a period of extreme fire danger (FFMC = 85.86, DC = 237.18) consistent with the highest fire occurrence year in the record. The multi-year FWI time series also correctly identifies December–February as the high-danger window and April–November as low-danger, matching the seasonal fire pattern.

Reviewer 1 correctly notes that correlation is not causation and that multiple linear regression is not an optimal tool for probabilistic event prediction. We acknowledge this limitation explicitly. The correlations presented here are diagnostic — they quantify the strength of association between climate variables and fire danger, not causal mechanisms. A rigorous probabilistic approach (e.g., logistic regression, Random Forest, or Bayesian network modelling) would require a substantially larger fire event database with consistent spatial coverage, currently unavailable for Sumapaz given the MODIS detection limitations. We recommend such analysis as a priority for future research (Section 8). Notwithstanding, the FWI system itself is a physically grounded model with validated predictive skill globally [20,23,26]; its application here goes beyond simple correlation by incorporating causal biophysical relationships between climate inputs and fuel moisture.

The spatial coarseness of ERA5 (~31 km) is a real constraint in Sumapaz's complex terrain, where temperature lapse rates, precipitation shadows, and valley-floor cold-air pooling create microclimatic diversity at scales of 1–5 km. ERA5 values represent area averages that likely underestimate peak FWI values in exposed ridgeline positions and overestimate them in humid valley bottoms. Downscaling ERA5 to local topographic context using a Digital Elevation Model-based lapse rate correction would improve FWI spatial accuracy and is feasible as a methodological improvement with existing open-source tools [27,43].

4.3. Risk Zoning Results in Regional Context

Our finding that 43.34% of Sumapaz faces Moderate risk and 3.70% High/Very High risk is broadly consistent with the general fire risk characterisation in the CLGR-CC Sumapaz local plan [6], which identifies the northern sector as the primary risk zone, and with Torres [44], who reported Moderate-to-High risk for comparable vegetation types in the Bogotá Eastern Hills. The spatial pattern of High and Very High risk matching the U. europaeus invasion zone is a novel finding not present in previous assessments and represents an actionable addition to the existing risk landscape.

Compared to pan-European wildfire risk studies such as Libertà et al. [41] and Bacciu et al. [52], Sumapaz's overall FWI values are relatively low (mean 0.78 vs. Mediterranean mean values of 15–40), reflecting the high humidity of Andean precipitation regimes. However, the 2010 peak values (FWI = 13.7) approach the lower bound of the High category used in European systems, suggesting that exceptional ENSO years generate fire danger approaching the levels routinely experienced in fire-prone Mediterranean ecosystems. This comparison underscores the importance of monitoring extreme years rather than mean conditions for operational fire management.

4.4. Limitations

The following limitations constrain the conclusions of this study:

- **MODIS detection uncertainty:** Active-fire detections underestimate true fire frequency due to smoke occlusion, vegetation canopy closure, and minimum detectable size (~0.1 ha). Counts presented here are conservative estimates of actual fire occurrence. Integration with high-resolution Sentinel-2 burned area products would improve completeness.
- **ERA5 spatial resolution:** The ~31 km ERA5 grid cannot resolve sub-grid topographic effects (temperature inversions, orographic precipitation). FWI values at specific ridgeline or valley-floor locations may diverge from the grid-cell average. Installation of automated weather stations within Sumapaz would allow local validation and correction.
- **Weighting coefficient justification:** Weights in Equations 1 and 2 were adopted from the IDEAM protocol [5] with the FWI weight (0.17) replacing the static susceptibility parameter. While IDEAM weights were derived from expert elicitation at national scale, their regional optimality for Sumapaz has not been formally tested. Sensitivity analysis of weight perturbations (±20%) would quantify the robustness of the risk classification.
- **Probabilistic vs. deterministic approach:** The risk index is deterministic (point estimate per grid cell). Probabilistic approaches such as Monte Carlo simulation or logistic regression would better characterise uncertainty in the final risk maps. We consider this a critical priority for future work.
- **Local validity:** The methodology is designed for and applied to Sumapaz specifically. Transferability to other localities requires re-calibration of the vulnerability weights to local socioeconomic conditions and validation of the FWI against local fire records.

4.5. Proposed Risk Management Strategies

The strategies presented here are directly grounded in the spatial risk assessment results. They are not generic recommendations applicable to any fire-prone landscape; rather, each strategy targets a specific causal factor and geographic zone identified in the risk analysis. This explicit diagnostic-to-prescriptive logic distinguishes this framework from prior Sumapaz risk documents [6,30]. The strategies are organised under three pillars of Colombia's National Disaster Risk Management Law (Law 1523/2012) [46]: Risk Knowledge, Risk Reduction, and Disaster Management (Figure 11). Feasibility scores from the multi-criteria assessment (Table 4 scale) are provided for each action set.

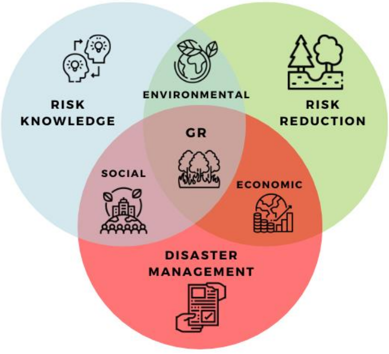

Figure 11. Conceptual framework for the comprehensive Vegetation Cover Fire (VCF) Risk Management strategy for the Sumapaz locality, structured around three intersecting pillars aligned with Colombia's National Disaster Risk Management Plan (PNGRD 2015–2030, Law 1523/2012). The three pillars — Risk Knowledge (Conocimiento del Riesgo), Risk Reduction (Reducción del Riesgo), and Disaster Management (Manejo de Desastres) — address the environmental, social, and economic dimensions of fire risk respectively. The overlapping areas of the Venn diagram indicate cross-cutting actions: the intersection of Risk Knowledge and Risk Reduction represents early warning and monitoring systems; the intersection of Risk Reduction and Disaster Management represents contingency planning; and the central intersection of all three pillars represents the integrated operational response capacity required for high and very high risk zones identified in Figure 10c. (Source: authors; adapted from PNGRD framework).

doi:10.20944/preprints202603.1832.v1

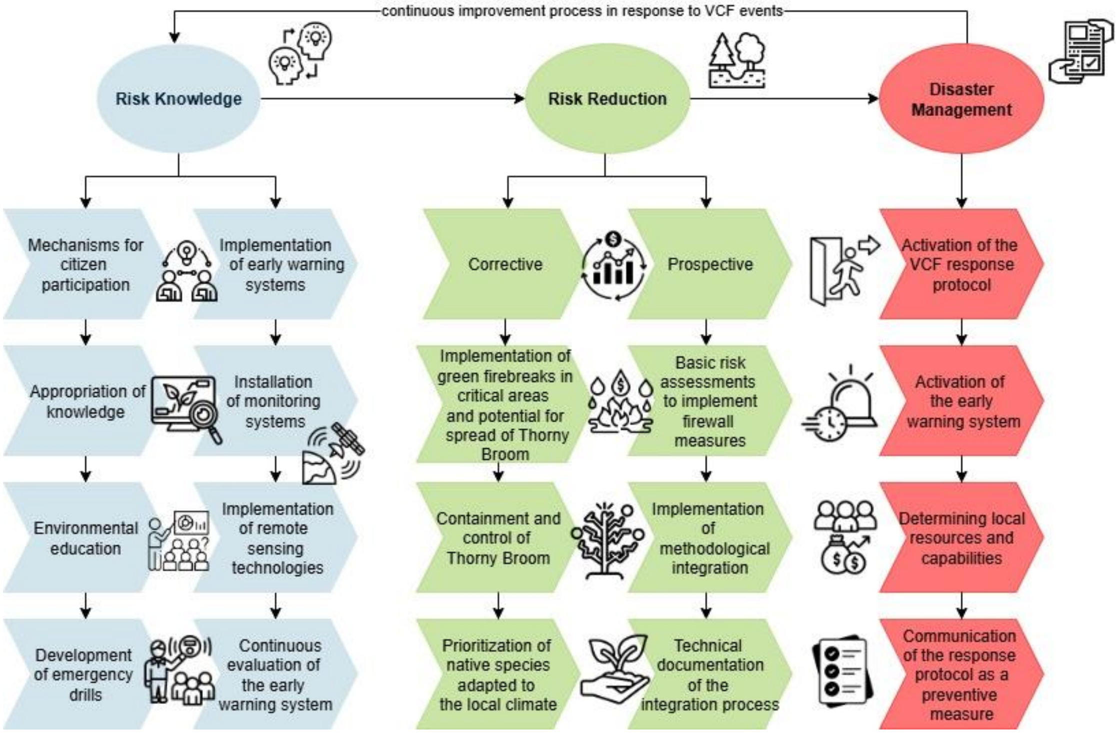

Figure 12. Detailed Risk Management Strategy diagram for Sumapaz, illustrating the full portfolio of 23 specific actions distributed across the three-pillar framework. Under Risk Knowledge: monitoring network expansion, FWI-based early warning system, invasive species surveillance, and community risk perception surveys. Under Risk Reduction: two sub-tracks are distinguished — Corrective measures (targeted at existing high-risk conditions, including U. europaeus mechanical and biological control, prescribed burn protocols, and firebreak establishment in the northeastern escarpments) and Prospective measures (oriented toward preventing future risk accumulation, including land-use planning, agroforestry buffer zones, and reforestation with native species). Under Disaster Management: incident command system activation, inter-agency coordination protocols, post-fire recovery planning, and community emergency response capacity building. Arrow flows indicate the temporal sequencing and feedback loops within the continuous improvement cycle. Actions are prioritised by multi-criteria feasibility score (Table 4). (Source: authors).

4.6. Pillar 1: Risk Knowledge

The evidence base developed in this study — fire occurrence maps, FWI time series, and risk zoning — constitutes the foundation of the risk knowledge pillar. Two strategy tracks are proposed:

Strategy 1.1: Community Engagement and Environmental Education (Feasibility score: Environmental = 5, Technical = 3, Economic = 4, Effectiveness = 5). The persistent recurrence of fire epicenters in agricultural zones strongly implicates human ignition (agricultural burning, land clearance) as a primary ignition source. Evidence from comparable Colombian localities [53,54] shows that structured community participation programmes reduce human-caused ignitions by 30–50% over 3–5 years when combined with incentive structures. Proposed actions: (a) multi-stakeholder risk awareness workshops integrating the locality's fire maps and FWI calendar into participatory planning; (b) environmental education programme for farmers on alternatives to burning (mulching, mechanical clearance); (c) regular fire simulation drills with local and institutional actors (minimum annually). Target groups: the ~1,200 residents of the northern sector.

Strategy 1.2: Early Warning System Implementation (Feasibility: E=5, T=3, Ec=3, Ef=5). The validated FWI model provides the meteorological backbone for an early warning system. When the monthly FWI forecast (derived from seasonal ERA5 forecasts) crosses the Moderate threshold (6.0), a pre-alert is issued to local emergency management authorities. When it crosses the High threshold (15.0), fire restriction protocols are activated. The system should be complemented by an environmental sensor network installed at the four identified hotspot locations (minimum: temperature, RH, wind speed, precipitation) to enable local-scale FWI calculation and real-time alert triggers. Integration with IDEAM's national climate forecast products and FIRMS satellite monitoring provides operational continuity.

4.7. Pillar 2: Risk Reduction

Risk reduction acts on the drivers of threat and vulnerability identified in the analysis, through both corrective actions (addressing existing risk) and prospective actions (preventing new risk formation).

Strategy 2.1 (Corrective): Green Firebreak Implementation in Critical Zones (Feasibility: E=5, T=5, Ec=4, Ef=5; total = 19/20 — highest-scoring action). The risk analysis identifies the northern epicenter as the priority zone for active structural intervention. Green firebreaks — plantations of native, low-flammability species — are proposed along the northern boundary of U. europaeus invasion, oriented perpendicular to the prevailing southeast wind direction to interrupt fire spread pathways. Species selection was based on the Bogotá Ecological Restoration Protocol [55] and local ecological expertise, prioritizing species with high moisture retention, dense canopy, deep root systems, and documented tolerance of post-fire conditions (Supplementary Table D3.1). Recommended species include: Escallonia paniculata (Tibar; altitude 2,500–2,900 m.a.s.l., moderately fire-tolerant, dense canopy), Clusia multiflora (Gaque; 2,800–3,300 m.a.s.l., high moisture retention), Baccharis latifolia (Chilco; pioneer on disturbed slopes), and Lupinus mirabilis (pioneer in post-fire páramo, nitrogen-fixing). Firebreak design: concave geometry aligned to topographic contours, width to be determined by local slope and wind modelling (minimum 20 m effective width recommended by Martínez [51]).

Strategy 2.2 (Corrective): Control and Containment of Ulex europaeus (Feasibility: E=5, T=3, Ec=3, Ef=5). Management of U. europaeus must comply with Colombian Resolution 0684 of 2018 (which mandates control of invasive species). Mechanical removal (cutting + root extraction) is the primary recommended method, followed by soil seeding with native species to prevent recolonisation. Herbicide application may be considered as a secondary tool under permit, given the sensitivity of páramo soils. Seed bank depletion requires a minimum 5–7 year treatment cycle due to the longevity of U. europaeus seeds. A dedicated monitoring programme with annual mapping is needed to track expansion into the modelled dispersal zone.

Strategy 2.3 (Prospective): Methodological Integration and Basic Risk Studies Update. The FWI-IDEAM integrated framework developed here should be formally incorporated into the updated CLGR-CC Sumapaz local plan as the standard risk assessment tool. This requires: (a) transfer of the methodology and code to IDIGER (Bogotá's district risk management institute); (b) annual updating of the risk maps using the previous year's FWI values; (c) extension of the vulnerability assessment to incorporate current land-use change dynamics from annual MapBiomas updates. The documentation package includes the full methodological technical file to ensure institutional continuity.

4.8. Pillar 3: Disaster Management

Disaster management addresses the reality that, despite prevention efforts, wildfires will continue to occur. The objective is to minimise impacts when fires do occur through faster detection, more coordinated response, and more rapid post-fire recovery.

Strategy 3.1: Activation of VCF Response Protocol (Feasibility: E=5, T=5, Ec=4, Ef=5). A structured four-phase response protocol is proposed: (i) Detection — real-time FWI monitoring + FIRMS satellite alerts + local sensor network triggers; (ii) Mobilisation — predefined activation of fire brigades with resource inventories updated by the local risk plan; (iii) Suppression — prioritised access routes based on road risk classification (Section 5.5), with aerial support pre-arranged for the 18.25 km of high-risk roads with no vehicle access; (iv) Monitoring and Closure — real-time fire perimeter tracking with post-fire damage assessment using Sentinel-2 Normalized Burn Ratio (NBR). The 63.82 km of low-risk roads provide the operational backbone for initial response; helicopter or UAV deployment is the required contingency for the high-risk zone.

Strategy 3.2: Post-Fire Ecosystem Recovery. Post-fire recovery in páramo ecosystems can span 10–30 years depending on fire severity and recurrence interval [7,56]. Priority actions include: (a) immediate erosion control on steep burned slopes (jute blankets, contour berms); (b) native species seeding using species from Table D3.1 prioritised for post-fire colonisation (especially Lupinus mirabilis, which recolonises quickly and fixes nitrogen); (c) exclusion of grazing in recovering areas for minimum 3 years; (d) long-term monitoring of recovering vegetation using MapBiomas annual maps and field plots.

5. Conclusions

This study has demonstrated that an integrated approach combining the dynamic Canadian Fire Weather Index with IDEAM's national vulnerability and risk zoning protocol produces a spatially explicit, operationally useful wildfire risk assessment for the Sumapaz locality — Colombia's most fire-affected and ecologically strategic rural district in Bogotá. The principal findings are:

- Sumapaz accounted for 64.9% of all VCF events in Bogotá (2001–2023), with 128 documented fires burning ~815 ha. Fire occurrence is strongly seasonal (78% in December–March) and spatially concentrated in four persistent hotspot epicenters, indicating landscape-level predispositions beyond interannual climate variability alone.
- The FWI correctly identifies the 2010 El Niño year as the peak fire danger period (FWI = 13.7; DC = 237.18 in January 2010), providing temporal validation of the meteorological model. No single climate variable is independently predictive; fire danger emerges from the synergistic interaction of precipitation deficit, temperature, solar radiation, and low specific humidity.
- Risk zoning reveals that 92.06% of the locality carries Moderate threat and 43.34% Moderate risk, concentrated in the northern agroforestry-forestry zone. Critically, 3.70% of the area — ~2,889 ha — is classified as High/Very High risk, geographically coinciding with the U. europaeus invasion zone and steep northeast-facing escarpments. This small but fire-intense zone should be the priority for active intervention.
- The invasive pyrogenic shrub Ulex europaeus (thorny broom) represents a specific and growing biological risk amplifier, with a modelled potential dispersal expansion of 467% from current coverage. Control and containment of this species is an urgent fire risk management priority independent of climate drivers.
- The proposed three-pillar risk management framework (Risk Knowledge, Risk Reduction, Disaster Management) provides a coherent set of spatially targeted, evidence-based strategies with quantified multi-criteria feasibility scores. The highest-priority actions — green firebreaks in the northern epicenter and an FWI-based early warning system — are both technically feasible and environmentally beneficial.
- Key limitations include MODIS detection underestimation, ERA5 spatial coarseness in complex terrain, and the deterministic nature of the risk index. Future work should prioritise probabilistic fire occurrence modelling, local weather station installation, and long-term validation of the proposed management interventions.

For Future Research

- Develop probabilistic wildfire occurrence models (logistic regression, Random Forest) using fire event data as the binary outcome variable, including FWI components, topographic indices, and land-use variables as predictors, to provide statistically robust estimates of fire probability.

- Integrate ERA5 data with a network of automated weather stations (AWS) deployed within the locality to allow local FWI calibration and validation, reducing the spatial coarseness limitation.
- Extend the analysis to include future climate scenarios (CMIP6 SSP2-4.5 and SSP5-8.5) to assess how projected changes in precipitation seasonality and temperature extremes may alter the FWI distribution and risk zoning by mid-century.
- Validate U. europaeus dispersal model predictions through field mapping campaigns and refine containment strategies based on observed spread patterns.
- Assess the effectiveness of implemented firebreaks and community engagement programmes through a before-after control-impact (BACI) monitoring design, providing empirical evidence for adaptive management.

For Policy and Management

- Formally incorporate the FWI-IDEAM integrated risk framework into Sumapaz's updated Local Risk Management and Climate Change Plan (CLGR-CC), establishing annual map updates as a standard output.
- Implement a community fire brigade programme with specific training for high-risk road access limitations, pre-positioning of suppression equipment at the four identified fire epicenters.
- Declare the U. europaeus control zone a priority intervention area under Bogotá's Environmental Management Plan, securing multi-year funding for mechanical removal and native restoration.
- Develop connectivity corridors of native species linking the northern and southern fire management zones to improve landscape-level fire resistance and promote ecosystem-based adaptation.

Author Contributions: All authors contributed equally to the development of the manuscript. They were jointly involved in the conception of the study, data collection and analysis, as well as in the writing, revision, and final approval of the article.

Funding: This research was funded by the Universidad de Cundinamarca, Colombia, under the internal research call *VIII Convocatoria Interna*, through the project titled *"Citizen Participation and Local Governance for the Formulation of Wildlife Conservation Strategies in Facatativá.*

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: MODIS FIRMS active-fire data are publicly available at https://firms.modaps.eosdis.nasa.gov/. ERA5 climate data are available through the Copernicus Climate Data Store at https://cds.climate.copernicus.eu/. MapBiomas Colombia land-cover data are available at https://colombia.mapbiomas.org/. IGAC cartographic data are available at https://geoportal.igac.gov.co/. Derived datasets (FWI time series, KDE outputs, risk maps) are available upon request to the corresponding author (kasanchez@ucundinamarca.edu.co), subject to approval by V. Ortiz and A. Quiroga.

Acknowledgments: The authors thank the Universidad de Cundinamarca for institutional support. We are grateful to Karel Sánchez for academic guidance throughout the project. We acknowledge the Copernicus Climate Change Service (C3S) for ERA5 data, NASA FIRMS for active-fire data, and MapBiomas Colombia for land-cover products. The authors also acknowledge the constructive comments of four anonymous reviewers whose detailed critiques substantially improved this manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Y. E. Capador Aguilar, G. P. González Angarita, and P. A. Suarez Daza, 'Analysis of Vegetation Coverage in Forest Fires Using Spectral Indices: Case Study of Eastern Hills (Bogotá, Colombia),' Avances Investigación en Ingeniería, vol. 18, no. 1, Apr. 2021, doi: 10.18041/1794-4953/avances.1.6931.
2. CDPMIF, 'Management Report — District Commission for Forest Fire Prevention and Mitigation. Mayor's Office of Bogotá, D.C.,' 2020.
3. I. Castillo Rojas, 'Forest Fire Risk Management, Sumapaz, Bogotá D.C. Analysis for the construction of participation-action strategies,' 2017.
4. G. Carlo and C. Nova, 'Application of a rural digital transformation model in the Sumapaz region to address environmental emergencies caused by forest fires,' 2021.
5. IDEAM, 'Protocolo para la Realización de Mapas de Zonificación de Riesgos a Incendios de la Cobertura Vegetal — Escala 1:100,000,' Bogotá, 2011.
6. CLGR-CC, 'Plan Local de Gestión del Riesgo y Cambio Climático CLGR-CC Sumapaz,' 2019.
7. Á. del C. Parra-Lara and F. H. Bernal-Toro, 'Cover fires and biodiversity: a look at the potential ecological impacts and effects on plant diversity,' El Hombre y la Máquina, no. 35, 2010.
8. D. Armenteras, 'Changes in the spatial patterns of burned areas in Colombia: What has happened in the first two decades of the 21st century?' Rev Acad Colomb Cienc Exactas Fis Nat, 2022, doi: 10.18257/raccefyn.1514.
9. B. López-Guevara, 'Spatio-temporal analysis of fires in northern and central South America: 2009-2019,' Agricolae & Habitat, vol. 4, no. 2, 2021, doi: 10.22490/26653176.4542.
10. D. Amaya and D. Armenteras, 'Fire Incidence on Vegetation in Cundinamarca and Bogota D.C. (Colombia) During the 2001-2010 Period,' Acta biol. Colomb., vol. 17, no. 1, 2012. Available: https://www.researchgate.net/publication/235933460
11. D. Armenteras-Pascual, J. Retana-Alumbreros, R. Molowny-Horas, R. M. Roman-Cuesta, F. Gonzalez-Alonso, and M. Morales-Rivas, 'Characterising fire spatial pattern interactions with climate and vegetation in Colombia,' Agric For Meteorol, vol. 151, no. 3, pp. 279-289, 2011, doi: 10.1016/j.agrformet.2010.11.002.
12. A. Hernández et al., 'Modes of climate variability: Synthesis and review of proxy-based reconstructions through the Holocene,' Earth Sci Rev, vol. 209, 2020, doi: 10.1016/j.earscirev.2020.103286.
13. IDEAM-UNAL, La Variabilidad Climática y el Cambio Climático en Colombia. 2018.
14. D. Armenteras-Pascual et al., 'Characterising fire spatial pattern interactions with climate and vegetation in Colombia,' Agric For Meteorol, vol. 151, no. 3, pp. 279-289, 2011.
15. D. Armenteras, 'Changes in the spatial patterns of burned areas in Colombia,' Rev Acad Colomb Cienc, 2022.
16. M. A. Ruiz-Ochoa et al., 'Climate variability for water management in the department of Casanare, Colombia,' Información tecnológica, vol. 34, no. 5, 2023, doi: 10.4067/S0718-07642023000500047.
17. L. C. López-Teloxa and A. I. Monterroso-Rivas, 'A Spatio-Temporal Analysis of the Frequency of Droughts in Mexico's Forest Ecosystems,' Forests, vol. 15, no. 7, 2024, doi: 10.3390/f15071241.
18. L. Vlassova et al., 'Analysis of the relationship between land surface temperature and wildfire severity in Landsat images,' Remote Sens (Basel), vol. 6, no. 7, 2014, doi: 10.3390/rs6076136.
19. Secretaría Distrital de Ambiente, 'Pilot plan to mitigate forest fires through a green belt with low-combustibility species in an urban-forest interface zone,' 2022.
20. D. M. Gaboriau et al., 'Drivers of Extreme Wildfire Years in the 1965-2019 Fire Regime of the Tłı̨chǫ First Nation Territory, Canada,' Ecoscience, vol. 29, no. 3, pp. 249-265, 2022, doi: 10.1080/11956860.2022.2070342.
21. V. Bacciu et al., 'Investigating the climate-related risk of forest fires for Mediterranean islands' blue economy,' Sustainability, vol. 13, no. 18, 2021, doi: 10.3390/su131810004.
22. C. Vaca, J. Calahorrano, and M. Manzano, 'Spatial and Temporal Analysis of Wildfires in Ecuador Using Remote Sensing Data,' Colombia Forestal, vol. 27, no. 1, 2024, doi: 10.14483/2256201X.20111.
23. C. E. Van Wagner and T. L. Pickett, 'Equations and Fortran Program for the Canadian Forest Fire Weather Index System,' Canadian Forestry Service, 1985.
24. L. Villers-Ruiz, E. Chuvieco, and I. Aguado, 'Application of the Canadian Fire Meteorological Index in a National Park in Central Mexico,' 2012.

25. K. Briones Monserrate, 'Desempeño del índice meteorológico de peligro Nesterov en Jipijapa, Manabí, Ecuador,' 2024.
26. D. Alves, M. Almeida, D. X. Viegas, I. Novo, and M. Y. Luna, 'Fire danger harmonization based on the fire weather index for transboundary events between Portugal and Spain,' Atmosphere (Basel), vol. 12, no. 9, 2021, doi: 10.3390/atmos12091087.
27. ECMWF, 'Fire danger indices historical data from the Copernicus Emergency Management Service,' 2024.
28. G. Libertà, J. S. Ayanz, D. Rigo, and H. Costa, 'Basic criteria to assess wildfire risk at the pan-European level,' 2018, doi: 10.2760/052345.
29. O. Rangel and A. Henry, 'Climate in the area of the Sumapaz Transect. Chapter 4,' 2008.
30. L. Penagos and M. López, 'Fire risk management and emergency response in Alto Magdalena: Institutional analysis and implementation of public policy during the period 2012-2019,' 2022.
31. NASA, 'Fire Information for Resource Management System (FIRMS).' https://firms.modaps.eosdis.nasa.gov/.
32. ERA5, 'Copernicus Climate Data Store.' https://cds.climate.copernicus.eu/
33. DANE, 'Population density.' https://geoportal.dane.gov.co/descargas/veredas/
34. IGAC, 'Protected areas, land use, and infrastructure data.' https://geoportal.igac.gov.co/
35. MapBiomas Colombia, 'Vegetation Cover.' https://colombia.mapbiomas.org/
36. W. Xu, M. J. Wooster, J. He, and T. Zhang, 'Improvements in high-temporal resolution active fire detection and FRP retrieval over the Americas using GOES-16 ABI,' Science of Remote Sensing, vol. 3, Jun. 2021, doi: 10.1016/j.srs.2021.100016.
37. H. N. Salsabila, A. F. Sahitya, and P. Mahyatar, 'Spatio-temporal pattern analysis of forest fire events in South Kalimantan using remote sensing and GIS,' IOP Conf. Ser. Earth Environ. Sci., 2020, doi: 10.1088/1755-1315/540/1/012011.
38. NASA-FIRMS, 'MODIS Collection 61 NRT Hotspot/Active Fire Detections MCD14DL.' https://earthdata.nasa.gov/firms
39. S. Kuter, N. Usul, and N. Kuter, 'Bandwidth determination for kernel density analysis of wildfire events at forest sub-district scale,' Ecol Modell, vol. 222, no. 17, pp. 3033-3040, 2011, doi: 10.1016/j.ecolmodel.2011.06.006.
40. B. M. Wotton, 'Interpreting and using outputs from the Canadian Forest Fire Danger Rating System in research applications,' Environ Ecol Stat, vol. 16, no. 2, pp. 107-131, 2009, doi: 10.1007/s10651-007-0084-2.
41. AEMET, 'Estadística del índice meteorológico de peligro de incendio (FWI),' 2019.
42. M. Del, C. Dentoni, and M. M. Muñoz, 'Fire Danger Assessment. Technical Reports,' Plan Nacional de Manejo del Fuego, 2012.
43. A. Mestre et al., 'Implementación progresiva de los códigos e índices del Sistema FWI para la predicción y vigilancia meteorológica del riesgo de incendios forestales en España,' 2014.
44. B. C. E. Torres, 'Zonificación de Riesgo por Incendio Forestal y Diseño de las Medidas Preventivas y Operativas para los Cerros Orientales de Bogotá D.C.,' 2022.
45. N. Martelo-Jiménez and O. V. Ríos, 'Forest fire risk assessment in the Santuario de Fauna y Flora Iguaque (Boyacá, Colombia),' Caldasia, vol. 44, no. 2, pp. 380-393, 2022, doi: 10.15446/caldasia.v44n2.91115.
46. Congreso de la República de Colombia, 'Ley 1523 de 2012 — Política Nacional de Gestión del Riesgo de Desastres,' 2012.
47. PNGRD, 'Plan Nacional de Gestión del Riesgo de Desastres. Una estrategia de desarrollo. Segunda actualización. 2015-2030,' 2015.
48. IDEAM, 'Informe de predicción climática a corto, mediano y largo plazo en Colombia,' 2024.
49. J. Barrera C and J. Rojas R, 'Plan de Prevención, Manejo y Control de las Especies del Retamo Espinoso (Ulex europaeus) y Retamo Liso (Genista monspessulana) en la jurisdicción de la CAR,' 2019.
50. D. Amaya and D. Armenteras, 'Fire Incidence on Vegetation in Cundinamarca and Bogota D.C. (Colombia) During the 2001-2010 Period,' Acta biol. Colomb., vol. 17, 2012.
51. S. M. Martínez, 'Diseño de patrones espaciales de cortafuegos para prevenir incendios forestales,' 2022.
52. V. Bacciu et al., 'Investigating the climate-related risk of forest fires for Mediterranean islands' blue economy,' Sustainability, vol. 13, 2021.

53. M. K. Galeano, 'Procesos Comunicativos en la Estrategia Educativa para la Gestión del Riesgo con Énfasis en la Prevención de Incendios Forestales implementada por la CVC en el Valle del Cauca,' 2018.
54. S. Moscoso J, 'Plan de gestión de riesgos para incendios forestales mediante SIG en Chongos Alto, Junín,' 2023.
55. A. M. Olivera, 'Protocolo Distrital de Restauración Ecológica. Guía para la restauración de ecosistemas nativos en las áreas rurales de Santa Fe de Bogotá,' 2000.
56. G. A. Jiménez, G. L. Urrego, and R. L. Toro, 'Evaluación del comportamiento de incendios de la vegetación en el norte de Antioquia (Colombia),' Colombia Forestal, vol. 19, no. 2, pp. 161-180, 2016, doi: 10.14483/udistrital.jour.colomb.for.2016.2.a03.