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Human and Natural Drivers of Wildfires in the Basque Country: Causes and Motivations (1995–2022)

Santiago Gaztelumendi [1]

1 - Basque Meteorology Agency (EUSKALMET), Vitoria-Gasteiz, Basque Country, Spain

Abstract

Understanding the drivers of wildfire ignition is essential for improving predictive models and early-warning systems, particularly in regions with high human activity such as the Basque Country. While natural factors like lightning, winds, temperatures, and drought contribute to fire risk, anthropogenic causes dominate ignition, shaping both the frequency and the area burned.Detailed knowledge of human-driven ignition causes, motivations, spatial, and seasonal patterns is critical to link historical wildfire behavior with environmental and meteorological conditions, and to improve strategies for integral wildfire risk management.This study examines a long-term dataset of 4,054 wildfire incidents, providing a detailed characterization of ignition causes, motivations, seasonal variability, and territorial patterns. These findings represent a first step to transition toward integrated wildfire risk systems that incorporate anthropogenic ignition precursors and fuel status into traditional meteorological wildfire risk frameworks..

1.Introduction

Understanding the complex interactions between human and natural drivers of wildfire ignitions is essential for improving early-warning systems and ignition forecasting models, particularly in regions characterized by intense anthropization and complex bioclimatic gradients. The Basque Autonomous Community (BAC) provides a critical and highly representative case study to address this challenge due to its acute socio-ecological and environmental heterogeneity, straddling the transitional boundary between the humid Atlantic Cantabrian front and the drier, warmer Mediterranean Ebro basin (Fig. 1). This bioclimatic pivot is physically driven by a rugged topography, where mountain ranges segregate the landscape into distinct fire environments defined by strong spatial and phenological gradients in weather, land-use, and vegetation fuel connectivity, within which different human practices condition ignitions (see Fig. 1), in a territory where less than 2% of wildfires are due to natural causes.

Previous research in the region has established a solid foundation on these environmental drivers, focusing on the characterization of critical fire-conducive synoptic patterns (Gaztelumendi et al. 2019), comparative macro-regional assessments within the Cantabrian arc (Gaztelumendi et al. 2025a), spatiotemporal pattern assessments (Gaztelumendi 2026b), and the evaluation of weather drivers (Gaztelumendi et al. 2026c, 2026d).

To transcend purely meteorological indicators, current operational frameworks (Gaztelumendi et al. 2020) require a migration toward comprehensive models that integrate human behavior as a central component of wildfire risk. This study addresses this need by analyzing the motivational and causal patterns of ignitions across the region's operational districts (Fig. 1). Through a combination of traditional data analysis and artificial intelligence/machine learning techniques (Gaztelumendi et al. 2025c), this research aims to optimize the Basque operational wildfire risk framework (Gaztelumendi et al. 2020, 2025b; GV 2025).

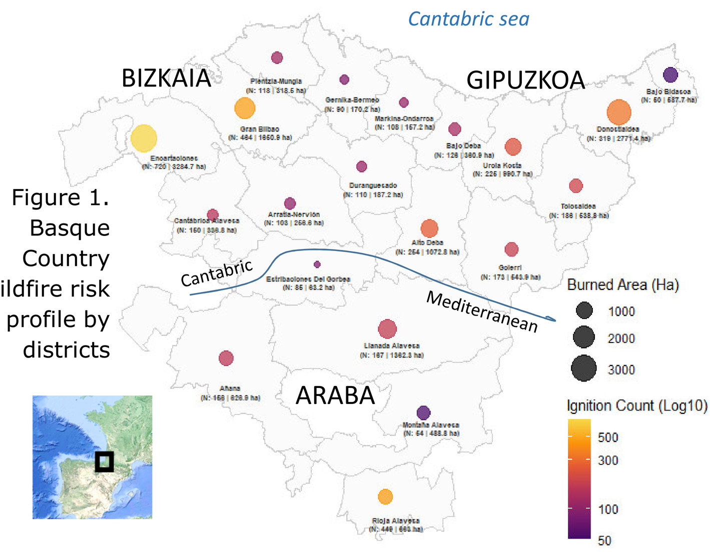

Figure 1. Basque Country wildfire risk profile by districts

2. Data and Methodology

2.1. Data

The study utilizes the official forest fire database of the Basque Country (EGIF matrix, 1995–2022), comprising 4,054 verified wildfire incidents. Extracted variables include Temporal, Geographic/Spatial, and Causal/Motivational attributes, alongside burned area characteristics. Data cleaning organized administrative boundaries into 3 Historical Territories (HT) and 20 operational districts (Fig. 1). The original 82 sub-cause/motivation codes (Table 1) were condensed into 19 consolidated intermediate categories (Table 2).

2.2. Exploratory and Descriptive Data Analysis

Absolute and relative proportions of ignitions and total burned area were computed and cross-analyzed for each HT across the 19 consolidated categories (Fig. 2). Absolute ignition frequencies were cross-tabulated across four independent temporal axes: annual trends, monthly seasonal dynamics, weekly labor cycles, and 24-hour diurnal cycles. Every temporal panel was stacked and colored by HT to account for geographic asymmetry, linking human activity schedules and regional reporting variations with localized landscape configurations (Fig. 3, 4, 5, and 6)

2.3. Characterization of ignition drivers and predictive modeling

To decode the behavioral mechanisms governing fire origins in each district, a supervised classification model was trained using a Random Forest algorithm based exclusively on spatial and temporal features. The dataset was partitioned into an 80% training set for model construction and a 20% independent testing set for validation.Predictor variables included raw temporal indices and engineered features: Hour, Month, Weekday, HT_Label, District_Label, Hour_Period (Morning, Afternoon, Evening, Night), Season_Label (Winter, Spring, Summer, Autumn), and a socio-labor binary indicator (Is_Weekend; YES/NO). The forest was built with 500 decision trees; the variables randomly sampled at each split (mtry) were optimized programmatically to maximize information gain and minimize out-of-bag error. Variable predictive power was evaluated via the Mean Decrease in Gini Index.

2.4. Actionable Knowledge Extraction via Decision Tree Paths

To translate multi-variable interactions into operational intelligence, the final RF model (Global Accuracy = 28.47%) was directly interrogated. Programmatic extraction of highly coherent terminal leaf-nodes through native conditional paths mapped out exactly 15 "Critical Ignition Scenarios" where spatial and temporal dimensions converge. Each scenario was filtered through quality control thresholds: a minimum empirical volume (Vol_N ≥ 10) independent fires per cell) and a minimum conditional predictive probability (Confidence ≥ 35%), discarding mathematical noise to provide direct deterministic rules.

2.5. Tools

Data curation, calculations, and spatial representations utilized R (R Core Team, 2026), leveraging the tidyverse ecosystem including dplyr (Wickham et al., 2023a), tidyr (Wickham et al., 2023b), ggplot2 (Wickham, 2016), purrr (Wickham & Henry, 2023), and stringr (Wickham, 2019) for data manipulation and visualization. Predictive modeling was implemented via the randomForest package (Breiman et al., 2024), while vector data processing and geospatial workflows were executed using the sf package (Pebesma et al., 2026).

3. Results and Discussion

3.1 Data preparation

The original dataset classifies all ignitions into five distinct series (see Tab 1) based on their cause and motivation : the 100 Series for lightning strikes, 200 for accidental human escapes, 300 for infrastructure failures, 400 for intentional arson, and 500 for unknown cases. To eliminate the statistical noise of marginal frequencies and establish robust blocks for socio-environmental description, core codes sharing identical spatial domains, seasons, and human activities were systematically aggregated. This processing step condenses the fragmented original sub-causes into exactly 19 intermediate consolidated categories.

This level of resolution represents the primary analytical focus of the study, capturing how distinct sectors and behaviors drive fire risk: 1. Natural Risk, 2. Unintentional Land Use and Negligence, 3. Technical and Infrastructural System Failures, 4. Deliberate Arson and Specific Motivations and 5. Uncertainty (see tab 2)

Table 1. Original natural and human drivers information

Id	Description
100	Lightning (Direct Natural Cause)
210	Other traditional agricultural burns
211	Agricultural stubble burns
212	Agricultural crop residue / pruning waste burns
213	Vineyard waste / shoot burns
214	Horticultural waste / small plot burns
216	Rural estate and boundary land clearing
220	General pasture management / livestock burns
221	Mountain brushwood and shrubland burns
222	Upland grass and herbaceous burns
230	Other operational forestry waste burns
231	Forestry logging slash and debris burns
240	General unmanaged bonfires / recreational fires
241	Recreational bonfires in established campsites
242	Fireworks and pyrotechnics
243	Power lines under construction
244	Other mountain sports and climbing activities
250	Smokers (discarded cigarette butts)
260	General household refuse and trash burns
261	Uncontrolled garbage dumping sites burns
262	Wildland-urban interface trash containers
270	Municipal landfill escapes
280	General interface property maintenance
281	Roadside ditch and embankment land clearing
282	Power transmission line right-of-way clearing
283	Railway corridor structural maintenance
284	Public highway infrastructure repairs
286	Other urban fringe development works
290	Miscellaneous accidental human causes
291	Children playing with fire
292	Hunters and anglers outdoor accidents
294	Backyard household activities
295	Other unclassified non-intentional sources
310	Railway brake friction and line mechanical failures
312	Catenary arcing and cargo train failures
320	Electrical distribution lines direct failures
322	Tree branches touching power lines under high wind
323	Defective grid insulators and wire snapping
324	Wildlife electrocution on grid infrastructure
325	Short-circuits in rural grid substations
330	General internal combustion engine accidents
334	Commercial vehicle mechanical breakdowns
335	Road traffic accidents and collisions
336	Roadside vehicle accidental fires
331	Agricultural grain harvesting machinery
333	Farm tractors and towed mechanical implements
351	Industrial timber harvesters
353	Mechanical crop balers and agricultural packagers
356	Tractor-mounted mechanical heavy mowers
340	Public military training activities
341	Live-fire exercises in military shooting ranges
361	Handheld angle grinders and metal saw sparks
362	Structural welding in rural properties
363	Portable handheld brush cutters and trimmers
370	Active forest defense and suppression backfires
371	Prescribed research burns / official technical fires
372	Off-season preventive containment fuel burns
399	Other unclassified mechanical and engine sources
400	Arson: Undetermined final motivation
401	Arson: Deliberate agricultural stubble burning
402	Arson: Deliberate rangeland pasture regeneration
403	Arson: Wildlife control and hunting habitat modifications
405	Arson: Real estate boundary and land disputes
404	Arson: Commercial timber industry disputes
441	Arson: Attempt to alter local timber market prices
443	Arson: Retaliation against forest community consorcios
451	Arson: Attempt to create civil unrest and public alarm
452	Arson: Animus against state reforestation programs
453	Arson: Protests against Protected Natural Areas
464	Arson: Personal vendettas and neighbor grievances
482	Arson: Opportunistic vandalism in picnic and park areas
483	Arson: Diagnosed mental illness / pyromania
484	Arson: Occult rituals and sect activities
499	Arson: Other unclassified anti-social behaviors
500	Total Undetermined Cause (No physical or human evidence)

Table 2. Unified 19 Causes and Motivations Categories

ID	Description
1.1	Natural Causes (Lightning): Ambient non-anthropogenic ignitions heavily clustered during localized convective summer storms (100).
2.1	Agricultural and Orchard Practices: Escapes from traditional stubble and crop residue clearing (210, 211, 212, 213, 214, 216).
2.2	Livestock and Pasture Management: Accidents during range management and mountain brushwood clearing (220, 221, 222).
2.3	Forestry Operations and Silviculture: Escapes from logging slash and debris removal in commercial timber stands (230, 231).
2.4	Roadside and Interface Maintenance: Incidents from road embankment clearing, ditch burning, and urban fringe pruning (280, 281, 282, 283, 284, 286, 295).
2.5	Waste Management and Refuse: Uncontrolled escapes from municipal landfills and informal domestic backyard dumping sites (260, 261, 262, 270).
2.6	Recreation, Ocio, and Domestic Use: Accidental fires from campsites, outdoor activities, pyrotechnics, and minor domestic activities (240, 241, 242, 243, 244, 250, 290, 291, 292, 294).
3.1	Rail Transport Corridors: Friction sparks from cargo train braking or electrical arcs from the catenary line (310, 312).
3.2	Electrical Distribution Networks: Grid short-circuits, defective insulator snaps, and branch contacts triggered by weather events (320, 322, 323, 324, 325).
3.3	Road Transport and Vehicles: Engine component overheating, roadside vehicle fires, and traffic collisions (330, 334, 335, 336).
3.4	Heavy Agricultural Machinery: Harvesting combines and balers working under intense operational stress in dry crop areas (331, 333, 353, 356).
3.5	Operations, Management, and Technical Works: Consolidates official prescribed suppression backfires with marginal records of handheld mechanical tools such as rural welding, angle grinders, or portable trimmers (340, 341, 351, 361, 362, 363, 370, 371, 372, 399).
4.1	Intentional - Undetermined Motivation: Verified deliberate fires where forensic teams could not isolate a specific personal or economic motive (400).
4.2	Intentional - Agricultural Practices: Arson acts tied to unauthorized crop or field burning (401).
4.3	Intentional - Livestock Practices: Arson explicitly aimed at removing mountain gorse and brush to force grass regeneration (402).
4.4	Intentional - Hunting Conflicts: Deliberate fires stemming from wildlife management disputes or hunter-vanguard friction (403, 411, 412).
4.5	Intentional - Land-Use and Property Disputes: Arson linked to boundary grievances, rural estate conflicts, or real estate classification shifts (405, 432, 433, 434).
4.6	Intentional - Anti-Social Behavior and Sabotage: Consolidates general pyromania and opportunistic vandalism by absorbing marginal frequencies related to timber price disputes and eco-protests against protected areas (404, 441, 443, 451, 452, 453, 464, 482, 483, 484, 499).
5.1	Total Causal Uncertainty: The historical volume of unclassifiable events (500).

3.2. Exploratory and Descriptive Analysis

Different aggregations, counts, and statistics are calculated for the 19 consolidated Causal-Motivational Fire Categories to characterize the dataset. The exploratory and descriptive analysis of the dataset is structured into two main components: first, an evaluation of territorial distributions and structural severity (Figure 2), followed by a multi-axis assessment of temporal and socio-labor cycles (Figures 3, 4, 5, and 6)

3.2.1. Exploratory and Descriptive Analysis

Ignition and Severity Asymmetry

Certain categories, specifically 3.2. Electrical Distribution Networks and 4.6. Intentional - Anti-Social Behavior & Sabotage, present low ignition frequencies (Column 1) but high proportional burned areas (Columns 2 and 4). This pattern is driven almost exclusively by records in Bizkaia.

This trend indicates a decoupling between the factors causing fire occurrence and the environmental conditions that influence subsequent fire suppression or propagation within the Atlantic basin.

Spatial Weight of Intentionally Caused Fires

The data confirm that deliberate fires represent the largest share of the total burned area in the Autonomous Community (Columns 3 and 4). 4.1. Intentional - Undetermined Motivation constitutes the primary source of burned area across the entire region, led by Gipuzkoa and Bizkaia. Meanwhile, 4.3. Intentional - Livestock Practices represents a substantial vector, characterized by high ignition frequencies in coastal territories (Column 1) combined with a moderate share of total burned area (Column 2).

Territorial Distribution of Agricultural Risks

Wildfire incidents linked to agricultural activities are concentrated in Araba. Both 2.1. Agricultural Practices and 3.4. Heavy Agricultural Machinery register their operational footprint and burned area almost entirely within this Mediterranean territory (Columns 1 and 2), while dropping to marginal levels in Bizkaia and Gipuzkoa. This distribution supports the development of differentiated risk models: focusing on harvesting machinery factors during the southern summer periods, and addressing traditional vegetation management during early spring periods in the north.

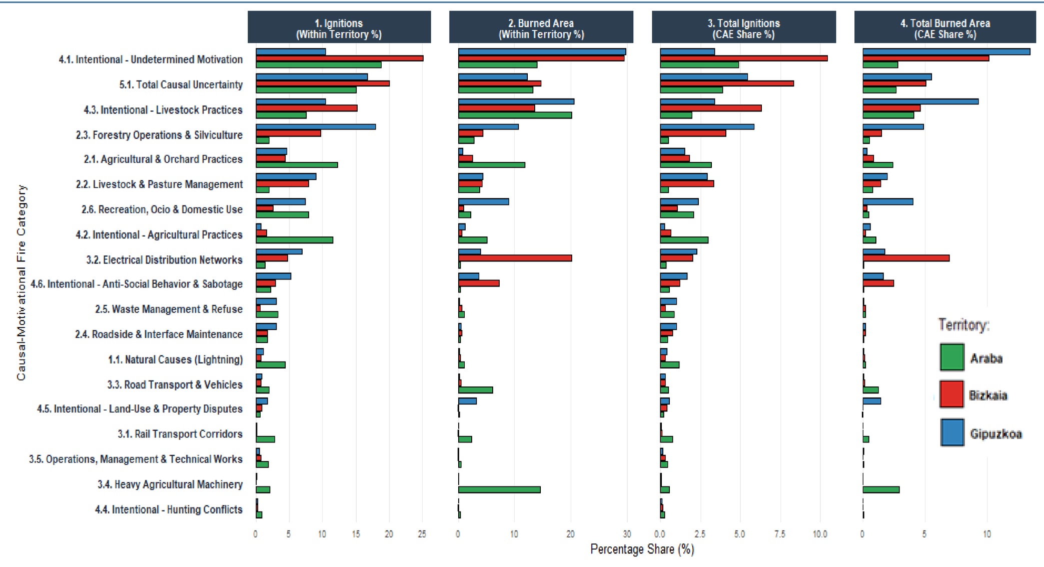

Figure 2. Multi-scale analytical matrix of causal motivational fire risk. scales.

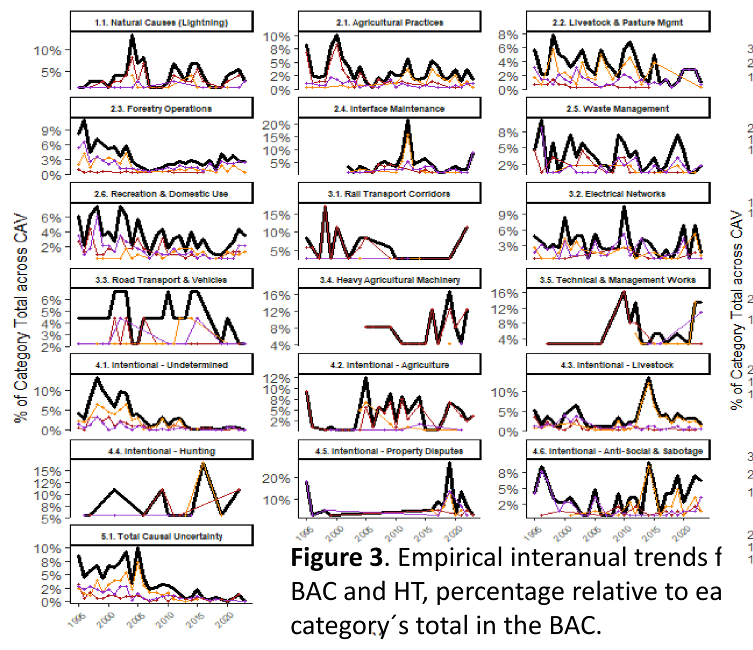

Figure 3. Empirical interanual trends f BAC and HT, percentage relative to ea category´s total in the BAC.

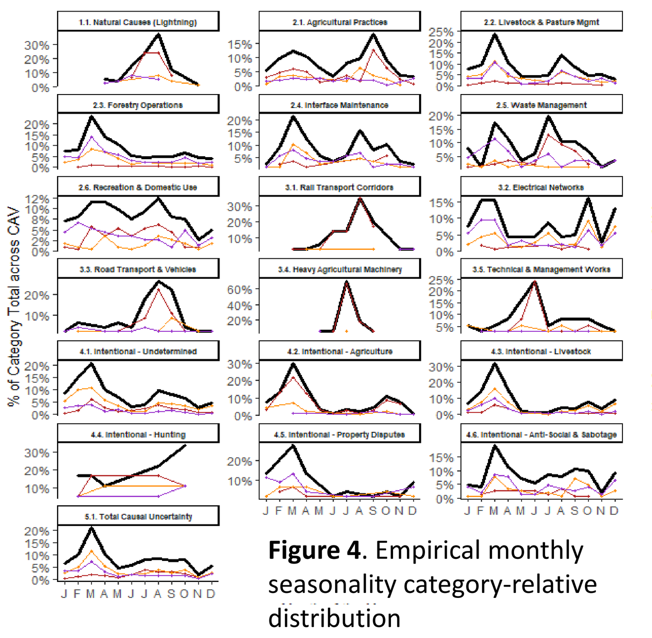

Figure 4. Empirical monthly seasonality category-relative distribution

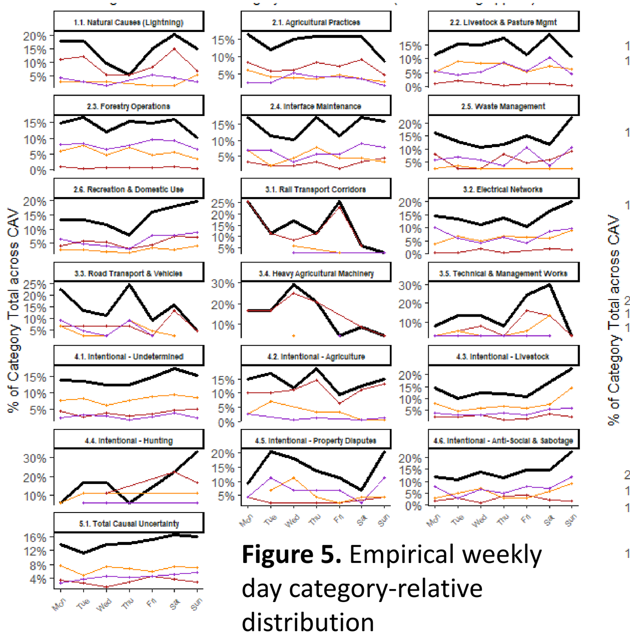

Figure 5. Empirical weekly day category-relative distribution

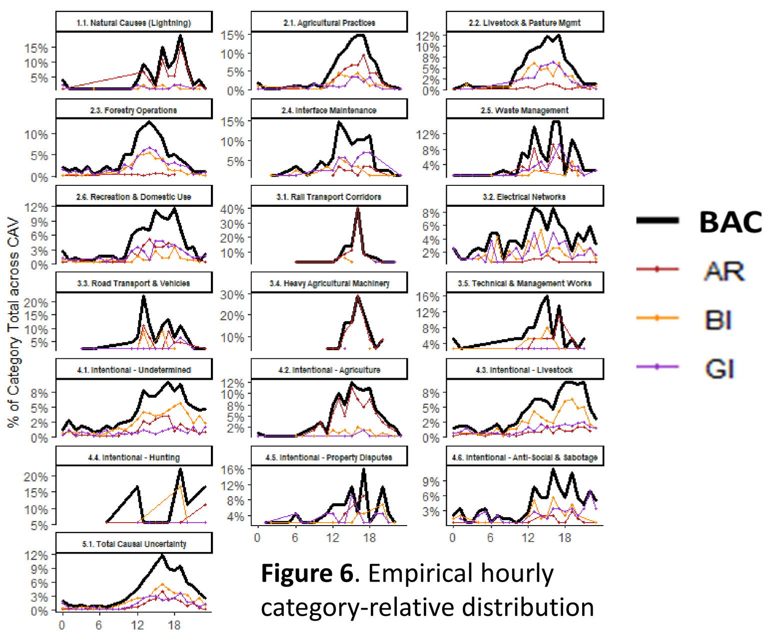

Figure 6. Empirical hourly category-relative distribution

3.2.2. Multi-Axis Temporal Patterns and Socio-Labor Cycles

Annual Trends (Fig 3)

Long-term interannual series show a general stabilization and reduction in both 4.1. Intentional - Undetermined Motivation and 5.1. Total Causal Uncertainty over the recent decades, indicating an improvement in reporting and forensic investigation accuracy.

Traditional livestock and pasture management practices (2.2) display noticeable structural variations and reductions in frequency in the post-2012 period, probably coinciding with the implementation of burning authorization frameworks.

Monthly Patterns and Seasonality (Fig 4)

Atlantic Spring Regime: Incidents related to 2.2. Livestock & Pasture Management and 4.3. Intentional - Livestock Practices concentrate heavily during March, driven almost exclusively by the records in Bizkaia (BI) and Gipuzkoa (GI) during pre-vegetative clearance periods.

Mediterranean Summer Regime: Conversely, 1.1. Natural Causes (Lightning) and 3.4. Heavy Agricultural Machinery failures peak strictly within July and August, presenting an operational footprint restricted to the southern agricultural plains of Araba (AR).

Weekly Behavior (Fig 5)

Socio-Labor Synchronization: Forest operations (2.3), rail transport (3.1), and agricultural machinery (3.4) frequencies align with standard working schedules, showing a reduction during weekends.

Weekend and Recreational Increments: Activities linked to 2.6. Recreation & Domestic Use and deliberate rangeland practices (4.3) display higher relative proportions on Saturdays and Sundays.

Hourly Behavior (Fig 6)

Circadian Distribution: Intentional livestock categories (4.3) and specific vandalism sectors (4.6) exhibit a marked concentration in the late afternoon and evening hours, specifically between 16:00 and 21:00, establishing a distinct nocturnal pattern compared to daytime operational accidents.

3.3. Random Forest

3.3. 1. Feature Importance and Global Performance

Global Accuracy:

The optimized ensemble model achieved a 28.47% global accuracy over the independent test set.

Predictive Power:

This performance is five times higher than random chance (1/19 ≈ 5.26%) for a 19-class classification problem.

Behavioral Signatures: High predictive accuracy confirms that human-driven ignitions are not random but follow stable spatiotemporal patterns.

Gini Key Drivers: District_Label emerged as the primary predictor in the Mean Decrease Gini ranking, followed by Hour and Month.

Macro-scale Stabilizers: Engineered features (Is_Weekend and Hour_Period) successfully reduced variance in the decision nodes.

3.3.2. Critical Ignition Scenarios via Decision Tree Paths

Direct interrogation of the best model forest's conditional paths programmatically isolated 15 critical ignition scenarios (Vol_N ≥ 10; Confidence ≥ 35%), uncovering high-resolution regional patterns (see tab 3). An graphical representation of some of then are shown in Fig 7.

Table 3. Critical Ignition Scenarios

District Baseline	Season	Weekend?	Time Period	Target Category (Prediction)	Conf. (%)
AR_RIBERAS	Autumn	NO	Afternoon	2.1. Agricultural Practices	73.1%
GI_GOIERRI	Spring	NO	Afternoon	2.3. Forestry Operations	63.6%
BI_ENCARTACIONES	Spring	NO	Morning	4.1. Intentional - Undetermined	62.5%
BI_ENCARTACIONES	Winter	YES	Night	4.1. Intentional - Undetermined	62.5%
BI_ENCARTACIONES	Spring	YES	Morning	4.3. Intentional - Livestock	55.6%
BI_ENCARTACIONES	Spring	YES	Evening	4.3. Intentional - Livestock	47.5%
BI_GRAN BILBAO	Winter	NO	Evening	4.1. Intentional - Undetermined	45.9%
BI_ENCARTACIONES	Winter	NO	Evening	4.3. Intentional - Livestock	44.2%
BI_ENCARTACIONES	Spring	NO	Evening	4.1. Intentional - Undetermined	43.9%
BI_ENCARTACIONES	Spring	YES	Afternoon	4.3. Intentional - Livestock	43.9%
GI_DONOSTIALDEA	Winter	NO	Evening	5.1. Total Causal Uncertainty	43.8%
BI_ENCARTACIONES	Spring	NO	Night	4.1. Intentional - Undetermined	41.4%
BI_ENCARTACIONES	Winter	NO	Afternoon	4.1. Intentional - Undetermined	39.0%
AR_RIOJA ALAVESA	Spring	NO	Afternoon	4.2. Intentional - Agriculture	37.5%
GI_DEBA GARAIA	Spring	NO	Afternoon	2.3. Forestry Operations	36.1%

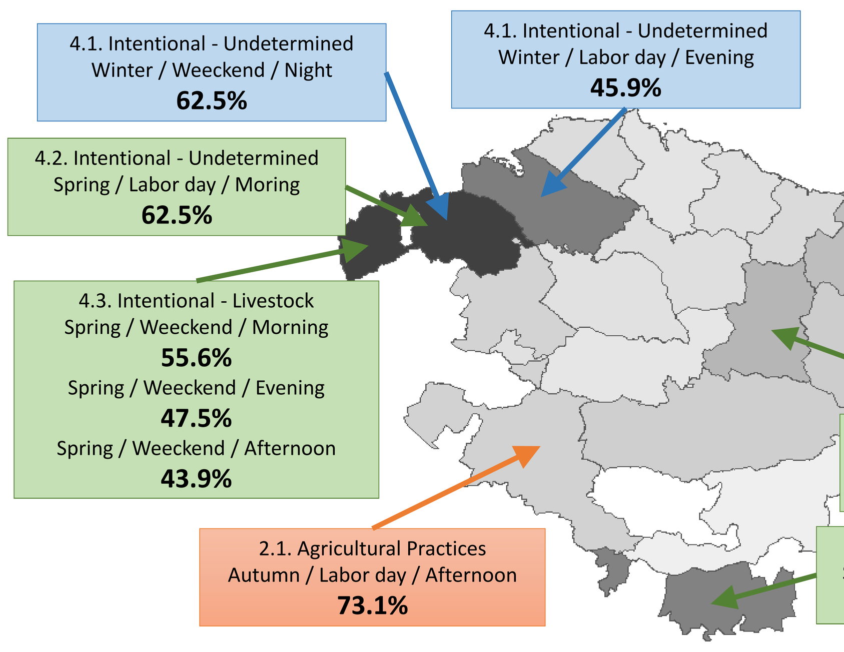

Figure 7. Spatial distribution and conditional probabilities of selected critical ignition scenario

4. Conclusions

- ✓ **Anthropogenic Dominance**: Human activity is the driver of wildfire regimes in the Basque Country, accounting for over 80% of total ignitions and 83% of total burned area, while natural lightning strikes remain at less than 2%.
- ✓ **Negligence vs. Arson Severity**: Negligent ignitions (uncontrolled agricultural/yard burns) represent the most prevalent source, dominating small-to-medium events, whereas deliberate arson episodes disproportionately dictate large-scale, high-severity fires.
- ✓ **Motivational Uncertainty**: Within intentional fires, 48% exhibit unknown or undetermined motivations, while identified targets are tied to livestock pasture management, agricultural friction, pyromania, localized land-use shifts and others.
- ✓ **Spatio-Temporal Asymmetries**: Negligence peaks during spring and summer high-risk periods, while deliberate ignitions display a bimodal spring-winter surge, notably driven by a specialized winter intentional-fire peak in Araba and western Bizkaia.
- ✓ **Territorial Scale Revision**: The analysis suggests that traditional provincial boundaries (HT_Label) may be insufficient for modeling localized fire dynamics. Consequently, the operational district scale (District_Label) consolidates as a preferable methodological alternative for structuring predictive risk frameworks
- ✓ **Predictive Model Calibration**: The optimized Random Forest framework reached a 28.47% global accuracy over 19 distinct categories, multiplying random chance by five and proving that human-driven ignition profiles possess precise, quantifiable signatures.
- ✓ **Operational Leaf-Node Extraction**: Programmatic path analysis isolated 15 critical ignition scenarios Day-to-day agricultural clearing marks maximum predictability in Riberas (73.1% Conf), and spring forestry operations dominate in Goierri (63.6% Conf).
- ✓ **Agricultural Sector (2.1 & 4.2):** Wildfire risk peaks in Araba/Álava during March, driven by stubble and boundary burning before spring sowing; this practice becomes highly hazardous when aligned with dry south wind episodes. A more pronounced, purely accidental risk window occurs in August due to machinery sparks during the cereal harvest.
- ✓ **Livestock Sector (2.2 & 4.3).** Concentrated in the Atlantic basin (Encartaciones), this sector shows a bimodal pattern driven by scrub clearance for pasture regeneration. The main peak occurs from February to April (highest in March), and a secondary one in October-November. Both windows exploit dry, intense south winds to ensure high-velocity biomass combustion
- ✓ **Reporting Quality Trends**: Reduction in unknown causes over recent decades.
- ✓ **Future work**: Upgrading current weather-based operational networks into integrated wildfire risk platforms by incorporating fuel status and anthropogenic ignition precursor models.

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EUSKO JAURLARITZA
GOBIERNO VASCO
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Contact info:
s-gaztelumendi@euskalmet.eus

EUSKALMET
Portal de Foronda, 41 (Edificio La Torre),
01010 Vitoria-Gasteiz.
Basque Country
www.euskalmet.eus

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