



Extreme Fire Thresholds and Hyperseverity in Bolivia's Forests (2002-2023): A Quantitative Assessment of Regulatory Effectiveness and Fire Governance

Guillermina Miranda Torrez

1. Institute of Ecology, Universidad Mayor de San Andrés, Bolivia

Abstract: The fire regime in Bolivia has undergone a transformation toward systemic hyperseverity, challenging institutional response capacities. This study establishes operational thresholds using robust statistical criteria (percentiles P_{95} and P_{99}) to characterize hypersevere events during the period 2009-2023 and critically assesses the effectiveness of the associated regulatory framework. The findings confirm a “heavy-tailed” distribution, with events such as those of 2010 and 2004 representing socio-ecological tipping points. A structural rupture in fire seasonality is identified, evidenced by the emergence of late extreme events in October and November 2023, which invalidates historical averages as a basis for public management. From the perspective of commons governance, the recurrence of exceedances beyond critical thresholds reveals a failure in institutional architecture, where certain policies have acted as catalysts for the expansion of the agricultural frontier. The study concludes that Bolivia faces a state of systemic risk that requires a transition from reactive suppression policies toward integrated landscape governance—eliminating regressive regulatory incentives and strengthening preventive territorial control.

Keywords: Hyperseverity, fire regime, statistical thresholds, environmental governance, Bolivia, extreme events

INTRODUCTION

In recent decades, forest fires across diverse biogeographical contexts have shifted alarmingly from recurrent ecological disturbances to extreme, high-magnitude events. This phenomenon is directly linked to the global climate crisis, structural transformations in land use, and critical failures in governance systems. From the perspectives of climatology and fire ecology, it is recognized that such events cannot be evaluated solely in terms of frequency; rather, their severity, persistence, and capacity to surpass critical thresholds within socio-ecological systems are the factors that determine their true impact (Bowman et al., 2009; IPCC, 2019). Scholars such as Müller et al. (2013) have demonstrated that, in Bolivia's lowlands, this dynamic has historically reflected a complex interaction between climatic variability and the aggressive expansion of the agricultural frontier. Within this framework, the concept of an “extreme event” acquires central analytical relevance, as it enables the identification of conditions that exceed the normal variability of the system (Coles, 2001; IPCC, 2012).

From a socio-ecological perspective, forest fires are not analyzed as isolated events but rather as integral components of a broader “fire regime,” defined by parameters of frequency and spatial magnitude. In Bolivia, research by Devisscher et al. (2016) highlighted that fire recurrence is exacerbated by forest fragmentation. Consequently, the fire regime

operates as a synthetic indicator of institutional capacity for territorial management (Pivello et al., 2021). To address this complexity, recent literature has advanced the concept of “compound events,” in which extreme impacts emerge from the convergence of multiple critical conditions (Leonard et al., 2014). Within this framework, hypersevere events are conceptualized in this study as episodes in which spatial magnitude, recurrence, and temporal persistence jointly exceed the defined statistical thresholds.

Despite the relevance of the issue, a significant conceptual and methodological gap has persisted in the analysis of wildfires in Bolivia. Although multiple descriptive studies are available, standardized quantitative criteria remain absent for identifying hypersevere events and distinguishing them from ordinary interannual variability. Cuellar et al. (2012) warned that this lack of parameters constrains the objective evaluation of public policies, since without explicit thresholds it is impossible to determine whether existing regulations have succeeded in reducing the occurrence of high-magnitude events. This argument aligns with evidence-based policy evaluation approaches, which require precise biophysical indicators to measure institutional performance (FAO, 2020; Ostrom, 2009).

Within the regulatory sphere, Bolivia’s 2009 Constitution established a robust framework for environmental protection. However, its translation into secondary legislation and operational instruments has been heterogeneous and, in certain cases, contradictory. The persistence of extreme fire events, according to FAO (2020), serves as a direct indicator of failures in the implementation of public policies. Researchers such as Cuellar et al. (2012) have demonstrated that, despite the existence of protective laws, the lack of interinstitutional coordination and the presence of economic incentives for deforestation have constrained the effectiveness of the post-constitutional regulatory framework.

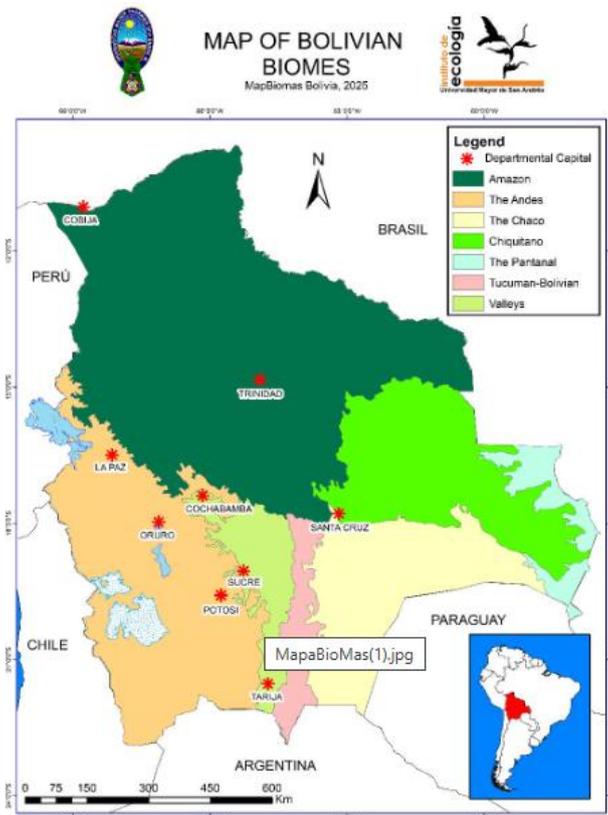
To address these deficiencies, the climatology of extremes suggests the use of advanced statistical tools. The IPCC (2012, 2022) has established that the application of high percentiles (P_{95} or P_{99}) provides a robust criterion for identifying critical conditions in environmental time series. In the Bolivian context, Anívarro et al. (2019) argued that the use of such thresholds enables a more precise classification of wildfire severity. Furthermore, assessing whether fire dynamics have changed significantly following specific regulatory milestones requires the identification of “structural breaks.” Procedures such as those developed by Bai and Perron (2003), together with non-parametric tests such as Mann-Kendall and Sen’s slope estimator (Helsel & Hirsch, 2002), allow for the detection of abrupt changes and trends in complex socio-ecological systems.

Against this backdrop, the present article aims to define extreme thresholds using robust statistical criteria and to establish an operational definition of hypersevere wildfire events in Bolivia during the period 2009-2023. The study seeks to critically evaluate the effectiveness of the regulatory framework and public policies associated with fire management.

To this end, we propose a methodological strategy based on the analysis of empirical distributions through the use of high percentiles (P_{95} and P_{99}), complemented by the detection of trends and structural breaks. This approach enables the linkage of extreme fire dynamics with institutional performance, transforming statistical thresholds into an analytical tool for the evaluation of public policy.

METHODOLOGY

The study was conducted using a quantitative, observational, and retrospective design, aimed at identifying extreme thresholds and establishing an operational definition of hypersevere wildfire events in Bolivia. The temporal framework was delimited to the period 2002-2023, based on datasets from Copernicus (Copernicus, n.d.) and the National Institute for Space Research (INPE, 2024). The spatial scope encompassed the national territory of Bolivia (Figure 1), incorporating the biomes heterogeneity of Amazon, The Andes, The Chaco, Chiquitano, The pantanal, Tucuman-Bolivian, and Valles (MapBiomias, 2025).



The principal variables analyzed were: (i) annual burned area (hectares), as a direct indicator of the spatial magnitude of fire, and (ii) the number of active fire hotspots, serving as a proxy for recurrence and intensity within the fire regime. These variables were selected due to their widespread use in the literature on fire ecology and the climatology of extremes, as well as their operational relevance in monitoring systems and decision-making processes (Bowman et al., 2009; FAO, 2020; IPCC, 2012).

Data on burned area and fire hotspots were obtained from satellite databases with continuous coverage and international validation, which are recurrently employed in regional and global wildfire studies. Prior to analysis, the time series were subjected to processes of cleaning, temporal homogenization, and consistency verification. Subsequently, annual series were constructed and, when pertinent, intra-seasonal aggregations were performed to capture the temporal persistence of events.

Extreme thresholds were defined through the analysis of empirical distributions of the selected variables. Following the approaches proposed by Coles (2001) and the IPCC (2012, 2019), high percentiles (≥ 95 th percentile) were employed as a statistical criterion to

delimit extreme events, under the assumption that these values represent conditions exceeding the normal interannual variability of the fire regime. The use of elevated percentiles provides a non-parametric approach, suitable for environmental series characterized by asymmetries, heavy tails, and departures from normality.

Based on these thresholds, an operational definition of hypersevere events was established, understood as years in which burned area and/or the number of fire hotspots simultaneously exceeded the defined extreme thresholds, or exhibited persistent exceedances across more than one relevant temporal unit within the dry season. This approach aligns with the logic of compound events, in which severity is explained by the convergence of multiple extreme indicators rather than by a single isolated variable (Leonard et al., 2014; Pivello et al., 2021).

To evaluate the temporal evolution of the fire regime and its relationship with the regulatory context, trend analyses were conducted using non-parametric Mann-Kendall tests and Sen's slope estimation. These methods are widely applied in climatological and environmental studies due to their robustness against outliers and non-normal distributions (Helsel & Hirsch, 2002). The tests enabled the identification of monotonic trends in the magnitude and recurrence of fires throughout the study period.

Complementary analyses of structural breaks in the time series were conducted, employing structural change tests to detect significant discontinuities in the mean or trend of the variables under study. This procedure enabled the exploration of potential breakpoints temporally associated with key regulatory milestones during the 2002-2023 period, following approaches proposed by Bai and Perron (2003) and Cleveland et al. (1990). The objective was not to establish direct causality, but rather to identify temporal coincidences between statistical changes in the fire regime and transformations within the institutional framework.

Finally, the statistical results were interpreted through a fire governance lens, integrating empirical evidence with an assessment of regulatory and institutional performance. The persistence or increase of hypersevere events was considered an indirect indicator of institutional vulnerability and limitations in the effectiveness of public policies, in line with theoretical frameworks on commons management and environmental governance (Ostrom, 1990; FAO, 2020). This integration allowed for an objective linkage between the dynamics of extreme fires and the critical evaluation of Bolivia's fire management regime.

RESULTS

Characterization of the Fire Regime and Determination of Thresholds

The analysis of raw data distributions revealed that both burned area and fire hotspots deviate from normality, a finding that technically supports the application of non-parametric statistical methods in this study. Through this approach, critical thresholds corresponding to the 95th (P_{95}) and 99th (P_{99}) percentiles were identified, establishing numerical limits for classifying a wildfire as "extreme" within the Bolivian context. Based on these criteria, years such as 2010, 2019, and 2023 consistently exceeded these metrics, consolidating themselves as the periods of greatest recorded severity.

Table 1: Extreme and High-Severity Wildfire Events in Bolivia (2002-2023): A Characterization Based on Burned Area Percentiles.

Percentile	Operational category	Month-Year	Burned Area (ha)	Interpretation
P95	Severe extreme event	aug-2019	2.149.785,15	Extreme Threshold Exceedance
P95	Severe extreme event	aug-2006	2.198.104,82	Extreme Threshold Exceedance
P95	Severe extreme event	aug-2005	2.201.539,35	Extreme Threshold Exceedance
P95	Severe extreme event	sep-2006	1.687.109,84	Extreme Threshold Exceedance
P95	Severe extreme event	sep-2019	2.225.645,52	Extreme Threshold Exceedance
P95	Severe extreme event	sep-2005	2.255.440,15	Extreme Threshold Exceedance
P95	Severe extreme event	sep-2007	2.423.882,81	Extreme Threshold Exceedance
P95	Severe extreme event	sep-2022	2.552.635,08	Exceedance Outside the Seasonal Peak
P95	Severe extreme event	oct-2023	1.866.521,56	Late-Season Extreme
P95	Severe extreme event	nov-2023	1.671.353,90	Late-Season Exceptional Extreme
P99	Hypersevere event	sep-2004	3.676.437,63	Exceptional Event
P99	Hypersevere event	sep-2010	2.707.039,06	Exceptional Event
P99	Hypersevere event	aug-2010	4.243.522,92	Maximum Hyper-Severe Event

The description of results for the period 2004-2023 is based on Table 1, which systematizes wildfire events in Bolivia that exceeded critical severity thresholds. Data were categorized using the 95th (P_{95}) and 99th (P_{99}) percentiles to statistically differentiate between extreme events and episodes of exceptional hyperseverity. Within the identification of hypersevere events, defined by the 99th percentile, the largest spatial magnitudes in the historical series were recorded. The historical maximum corresponds to August 2010, identified as the most hypersevere event, with a burned area of 4,243,522.92 hectares. Likewise, the events of September 2004 (3,676,437.63 ha) and September 2010 (2,707,039.06 ha) complete this category of exceptional episodes, marking the most critical peaks of ecological impact in Bolivia.

Under the 95th percentile threshold, ten months were grouped as exceeding the extreme limit, predominantly characterized by strong seasonal concentration. Most of these events occurred during August and September, with notable records in 2005, 2006, 2007, 2019, and 2022, where affected areas ranged between 1.68 and 2.55 million hectares. However, the results also reveal significant late-season anomalies in 2023, representing a rupture in the historical seasonal pattern. The months of October and November 2023, with burned areas of 1,866,521.56 ha and 1,671,353.89 ha respectively, were classified as late extreme and exceptional events.

The systematization of these data reveals that, although the greatest recurrence of extreme events is concentrated in the peak of the traditional dry season (August and September), the emergence of high-magnitude records in November 2023 demonstrates a prolongation of severity beyond conventional historical ranges. This operational classification constitutes the fundamental quantitative basis for critically assessing whether

the current regulatory framework possesses the flexibility required to respond to large-scale events occurring outside the traditional burning months.

Identification of Hypersevere Events

The joint comparison of extreme percentiles for burned area and fire hotspot recurrence allowed the identification of differentiated severity patterns and the isolation of compound hypersevere episodes, characterized by the simultaneous coincidence of high spatial magnitude and elevated ignition frequency.

Table 2: Extreme and Hyper-Severe Wildfire Events Based on Burned Area and Hotspot Recurrence in Bolivia

Month-Year	Burned Area (ha)	Surface percentile	Hotspots	Hotspot Percentile	Operational Classification
sep-2004	3 676.437,63	P99	30.565,00	P99	Compound Hyper-Severe Event
aug-2010	4.243.522,92	P99	34.574,00	P99	Compound Hyper-Severe Event
sep-2010	2.707.039,06	P95-P99	25.482,00	P95	Severe Extreme Event
sep-2022	2.552.635,08	P95	15.901,00	P95	Severe Extreme Event
sep-2007	2.423.882,81	P95	28.192,00	P95	Severe Extreme Event
sep-2005	2.255.440,15	P95	20.499,00	P95	Severe Extreme Event
sep-2019	2.225.645,52	P95	16.394,00	P95	Severe Extreme Event
aug-2005	2.201.539,35	P95	16.596,00	P95	Severe Extreme Event
aug-2006	2.198.104,82	P95	16.773,00	P95	Severe Extreme Event
aug-2019	2.149.785,15	P95	14.412,00	P95	Severe Extreme Event
sep-2006	1.687.109,84	P95	–	–	Severe Extreme Event (Burned Area)
oct-2023	1.866.521,56	P95	–	–	Late-Season Severe Extreme Event
nov-2023	1.671.353,90	P95	–	–	Late-Season Severe Extreme Event

Note: This table summarizes events that exceeded the extreme percentiles for burned area and hotspots. The 95th percentile (P95) defines severe extreme events, while the 99th percentile (P99) identifies hyper-severe events. Compound hyper-severe events are defined as months in which both variables simultaneously exceeded their highest thresholds. Missing values (–) indicate that the corresponding threshold for that variable was not exceeded. The recurrence of events in September confirms this month's central role as the core of the critical fire season, while events in October and November demonstrate a late-season extension of fire severity.

Table 2 systematizes wildfire episodes in Bolivia that, due to their magnitude and recurrence, exceeded statistical thresholds of normality, categorizing them according to their territorial impact. The study employs two principal metrics to define severity: burned area (in hectares) and the number of fire hotspots. Within this framework, *Severe Extreme Events* (P_{95}) are defined as months falling within the upper 5% of the historical series, while *Hypersevere Events* (P_{99}) represent the 1% most critical and devastating cases. The highest alert level corresponds to *Compound Hypersevere Events*, in which both burned area and hotspots simultaneously exceed the 99th percentile.

In Bolivia's recent history, the table identifies two critical moments, termed "Disaster Milestones," that reached the P_{99} threshold. August 2010 represents the historical maximum, with 4.24 million hectares burned and more than 34,500 hotspots detected. September 2004 stands as the other major compound hypersevere event, with 3.67 million hectares affected.

Regarding temporal patterns and the critical window, the results indicate a marked centrality of September, as seven of the thirteen listed events occurred in this month, consolidating it as the core of the highest-risk season. Notably, in 2019 both August and September surpassed the P_{95} threshold, with a combined impact exceeding 4.3 million hectares. A key finding is the trend toward risk prolongation through late-season events, as observed in October and November 2023. These months were classified as "Late Severe Extreme Events," suggesting a shift in the temporal dynamics of wildfires extending beyond the traditional dry-season months.

Finally, the analysis reveals specific cases—such as September 2006 and November 2023—where the classification of an extreme event is assigned solely on the basis of burned area, without fire hotspots reaching the P_{99} threshold. This dissociation indicates the occurrence of wildfires of large spatial magnitude that, nevertheless, may involve a comparatively lower number of ignition fronts detected simultaneously.

Trend Analysis and Structural Breaks

For the analysis of trends and structural breaks, the non-parametric Mann-Kendall (MK) test and Sen's slope estimator were applied to evaluate both the global (annual) trend and the seasonal (monthly) trend of burned area.

The analysis of the annual trend of burned area in Bolivia (2009-2023), using the Mann-Kendall test and Sen's slope, reveals the absence of a statistically significant monotonic behavior throughout the analyzed period. At the global level, the statistic $S=-21$ and the normalized value $Z=-0.564$ ($p=0.573$) confirm that the trend is not significant at the $\alpha=.05$ level, while Sen's slope of $-22,468 \text{ ha}\cdot\text{year}^{-1}$ (equivalent to the annual value of -640.29 in the hotspot table) indicates a very weak average decrease, insufficient to sustain a systematic change in the interannual regime. From a climatological perspective, these results demonstrate that the annual signal is dominated by high variability and the occurrence of isolated extreme events of great magnitude, which, by lying in the tails of the distribution, mask any persistent linear trend and prevent the identification of a sustained process of progressive intensification or attenuation of the affected area.

The seasonal trend analysis (Table 3) using the Mann-Kendall test indicates the absence of a significant trend in monthly burned area for the analyzed period, with a statistic $S=98$, a normalized value $Z=0.790$, and a significance level $p=.430$. Although the seasonal Sen's slope of $157 \text{ ha}\cdot\text{year}^{-1}$ shows a positive sign, its magnitude is small and statistically indistinguishable from zero, suggesting that no systematic change exists once seasonality is controlled for. From an operational standpoint, these results confirm that fire dynamics in Bolivia are mainly conditioned by intra-seasonal variability and isolated hyper-severe episodes rather than a sustained linear increase, as evidenced by the high dispersion of standard errors and the wide confidence intervals recorded in peak activity months such as August and September.

Table 3: Seasonal and annual trend analysis of affected area using Mann-Kendall and Sen's slope estimator (2002-2023).

Month	Standard Error	Kendall (τ)	Confidence Intervals		Sen's Slope	Limits	
			Lower bound	Upper bound		Lower bound	Upper bound
Jan	5.751,83	9.460,92	-4.614,96	4.845,96	482,16	-23.870,04	22.152,78
Feb	2.807,42	4.617,79	-2.193,39	2.424,39	407,85	-11.205,18	16.979,50
Mar	4.089,79	6.726,97	-3.247,99	3.478,99	431,27	-19.362,21	18.804,10
Abr	6.972,24	11.468,31	-5.618,65	5.849,65	67,46	-43.811,84	39.969,44
May	11.095,22	18.250,01	-9.009,50	9.240,50	-617,74	-73.134,21	60.061,50
Jun	24.480,28	40.266,48	-20.017,74	20.248,74	583,48	-159.534,33	169.408,62
Jul	136.703,81	224.857,76	-112.313,38	112.544,38	-1.327,31	-512.604,91	716.079,87
Aug	498.435,21	819.852,96	-409.810,98	410.041,98	-42.011,77	-3.420.822,09	3.883.647,65
Sep	400.257,00	658.364,21	-329.066,61	329.297,61	-15.844,88	-1.446.391,61	3.015.675,30
Oct	232.733,58	382.812,68	-191.290,84	191.521,84	14.032,24	-1.129.061,70	1.668.262,81
Nov	125.319,96	206.132,99	-102.950,10	103.182,00	2.465,00	-389.712,82	1.127.344,42
Dec	13.065,12	21.490,20	-10.629,60	10.860,60	654,71	-67.703,35	74.593,89
Annual	955.459,11	1.571.590,38	-785.679,69	785.910,69	-22.468,05	-6.063.635,28	7.225.969,06

Note: Analysis performed with a significance level of $\alpha = .05$ and 231 data pairs for the calculation of the slopes.

During the period analyzed between 2002 and 2023, trend analysis using the Mann-Kendall test and Sen's slope estimator revealed a complex dynamic characterized by the absence of uniform secular changes at the annual level. After evaluation at a significance level of $\alpha = .05$, it was determined that no month of the year exhibited a statistically significant trend for the burned area variable. Although both positive and negative slope values were recorded, in all cases the confidence intervals included zero, preventing confirmation of a systematic direction of change over time.

A first group of months with non-significant trends of low magnitude includes the first quarter and the transitional months of April and December. Between January and March, consistently positive Sen's slopes were observed, ranging between 407.85 and 482.16. However, the internal variability of the data produced negative lower bounds, as seen in January with a value of -23,870.04, classifying these increases as non-significant. Meanwhile, April and December showed the lowest positive slopes in the series, with 67.46 and 654.71 respectively, reflecting relative stability in the affected area during these periods.

On the other hand, a segment of high variability and uncertainty was identified, encompassing the periods of greatest activity, where the magnitude of the standard errors invalidated any interpretation of linear trend. At the peak of the season, represented by August and September, the deepest negative slopes of the study were recorded, with values of -42,011.77 and -15,844.88, respectively. However, these months exhibited massive standard errors, reaching 498,435.21 in August, which resulted in extremely wide confidence intervals spanning millions of surface units in both directions. Similarly, October and November showed a nominal reversal toward positive slopes of 14,032.24 and 2,465.00,

but continued to display high statistical dispersion and standard errors exceeding 125,000, confirming that the affected area in the last quarter was subject to stochastic extreme events rather than a predictable pattern.

At the global level, the annual series recorded a Sen's slope of -22,468.05. Despite this negative value, the trend was defined as non-significant, given that the confidence interval ranged between -6,063,635.28 and 7,225,969.06. This extreme symmetry around zero, supported by a standard error of 955,459.11, demonstrated that the affected area in the study region was dominated by cyclical interannual variability, without showing a statistically valid secular increase or decrease over the past two decades.

Table 4 presents the seasonal and annual trend analysis of fire hotspots in Bolivia for the period 2002-2023, using the non-parametric Mann-Kendall statistical test and Sen's slope estimator. This analysis is essential for identifying whether there is a sustained increase or decrease in the occurrence of fires over time.

Table 4: Seasonal and annual trend analysis of fire hotspots using the Mann-Kendall test and Sen's slope estimator (2002-2023).

Month	Standard Error	Kendall (τ)	Confidence Intervals		Sen's Slope	Limits	
			Lower bound	Upper bound		Lower bound	Upper bound
Jan	37,87	62,28	84,36	146,64	5,45	-0,37	12,45
Feb	23,08	37,96	96,52	134,48	3,00	1,67	4,23
Mar	27,91	45,91	92,54	138,45	3,13	1,43	5,60
Abr	78,05	128,39	51,34	179,69	5,31	-17,00	25,21
May	179,32	294,96	-31,98	262,98	15,25	-994,00	841,00
Jun	381,70	627,84	-198,42	429,42	23,67	-2.027,00	1.955,00
Jul	97.804,24	160.873,65	-80.321,33	80.552,33	2,69	-3.577,00	716.079,87
Aug	3.796,23	6.244,25	-3.006,62	3.237,62	-22,00	-27.779,00	30.814,00
Sep	3.379,73	5.559,16	-2.664,08	2.895,08	-270,47	-13.356,00	21.402,00
Oct	1.375,33	2.262,21	-1.015,61	1.246,61	-161,76	-4.427,00	8.146,00
Nov	831,40	1.367,53	-568,27	799,27	-4,36	-4.706,00	5.312,00
Dec	161,57	265,75	-17,38	248,38	8,86	-810,00	1.082,00
Annual	7.800,41	12.830,53	-6.299,76	6.530,76	-640,29	-51.357,00	59.087,00

Note: Analysis performed with a significance level of $\alpha = .05$ and 231 data pairs for the calculation of the slopes.

The analysis of monthly behavior of fire hotspots, detailed in Table 4, allows the identification of significant variations in trend intensity through Sen's slope. During the first half of the year, consistent positive slopes were recorded between January and June, with notable increases in May (15.25) and June (23.67), suggesting a gradual rise in the presence of fire hotspots at the onset of the dry season. However, in the months of historically highest activity, unexpected negative trends were observed, with slopes of -22.00 in August and

more pronounced declines in September (-270.47) and October (-161.76), resulting in an aggregated annual value of -640.29.

The robustness of these data is conditioned by extremely high interannual variability, reflected in exceptionally large standard errors during the peak of the season, specifically in July (97,804.24), August (3,796.23), and September (3,379.73). This uncertainty is manifested in most months through confidence intervals that cross the zero value, with negative lower bounds and positive upper bounds; a critical example is September, where the lower limit is -13,356.00 and the upper reaches 21,4025.00. The calculations, performed at a significance level of $\alpha = .05$ and based on 231 data pairs, provide a solid statistical framework for the temporal analysis of the fire regime.

Finally, this temporal evolution provides key evidence for meeting the objectives of the research, since the negative slopes in peak months, combined with the high standard error, indicate that the Bolivian system does not follow a constant reduction. On the contrary, the regime is characterized by the occurrence of sporadic extreme events of great magnitude that distort the linear trend. This behavior reinforces the technical need to employ percentiles (P_{95}/P_{99}), rather than simple averages or trends, to accurately evaluate the effectiveness of the regulatory framework and public policies associated with fire management.

Relationship Between Fire Hotspots and Affected Area (2002-2023)

The relationship between fire hotspot trends and affected area for the period 2002-2023 revealed a complex dynamic, in which the increase in the number of ignitions did not always translate into a proportional increase in the impacted area. A marked divergence was observed in the statistical significance of both variables; while fire hotspots showed significant upward trends during February (3,000) and March (3,133), with confidence intervals excluding zero, the affected area did not reach significance levels in the same period. Although the slopes for affected area in February and March were 407,851 and 431,269 respectively, their negative lower bounds invalidated any robust statistical trend.

During the period of high variability (August-September), both variables coincided in showing high volatility, though with different magnitudes. A nominal synchrony was recorded, characterized by negative Sen's slopes for both fire hotspots and affected area in August ((-216) and (-42,011.77)) and September ((-270.47) and (-15,844.88)). However, the affected area registered massive standard errors in August (498,435.21) compared to fire hotspots (3,796.23), indicating that the extent of burned areas was far more sensitive to sporadic extreme events, such as intense droughts linked to the ENSO phenomenon, than to the simple count of individual hotspots.

At the annual level, the analysis of the overall rate of change demonstrated that both variables maintained a stable relationship without a defined trend. The annual series of fire hotspots presented a slope of (-640.29), while the affected area recorded a slope of (-22,468.05). In both cases, the trends were classified as non-significant, since the confidence intervals encompassed ranges that included zero, demonstrating that interannual variability predominated over any long-term linear change during the two decades analyzed.

Finally, the comparison of these results suggested the existence of a “seasonal decoupling.” It was determined that, although there was a real and constant increase in ignition frequency during the first quarter of the year, the extent of fires failed to establish a clear trend in that same period. This phenomenon could be attributed to limiting factors, such as residual vegetation moisture, which may have slowed the spread of flames despite the greater number of detected hotspots. In conclusion, the analysis confirmed that fire risk increased in terms of frequency at the beginning of the year, but severity in terms of affected area continued to depend on stochastic climatic volatility.

Temporal Relationship with the Regulatory Framework - Integration with the Governance Approach

This subsection (Table 5) presents the temporal coincidence between surface data (ha) and the regulatory framework (laws and supreme decrees).

Table 5: Persistence of hyper-severe events as indicators of institutional vulnerability in fire management.

	Regulation Date	Regulatory Milestone (Law/Supreme Decree SD)	Month /Year of the event	Burned Area (ha)	Interpretation (P_{95} Threshold)
Historical Milestones	19oct2006	Law N° 3501	Aug 2006	2.198.104,82	Severe Event Extreme
	28nov2006	Law N° 3545	Sep 2006	1.687.109,84	Severe Event Extreme (Burned Area)
Highly Regressive	25abr2019	Law N° 1171	Aug 2019	2.149.785,15	Severe Event Extreme
			Sep 2019	2.225.645,52	Severe Event Extreme
	10jul2019	SD 3973	Aug 2019	2.149.785,15	Severe Event Extreme
			Sep 2019	2.225.645,52	Severe Event Extreme
Administratively Neutral	10feb2010	SD 429	Aug 2010	4.243.522,92	Compound Hyper-Severe Event
			Sep 2010	2.707.039,06	Severe Event Extreme
	02aug2007	SD 29215	Sep 2007	2.423.882,81	Severe Event Extreme
Corrective or Environmental	18may2022	SD 4719	Sep 2022	2.552.635,08	Severe Event Extreme

	09nov2023	Law N° 1525 	Oct 2023	1.866.521,56	Late-Season Severe Extreme Event
			Nov 2023	1.671.353,90	Late-Season Severe Extreme Event
	29nov2023	SD 5074 	Oct 2023	1.866.521,56	Late-Season Severe Extreme Event
			Nov 2023	1.671.353,90	Late-Season Severe Extreme Event

Note: Authors' own compilation based on regulatory milestones and burned area data.

The findings of the research identified that the persistence of extreme-severity events functioned as a central indicator of institutional vulnerability in fire management in Bolivia. It was determined that, regardless of the type of regulation enacted during the analyzed period, the burned area systematically exceeded the statistical threshold of the 95th percentile (P95), predominantly classified as “extreme-severe” events. This trend has been evident since the establishment of baseline severity levels between 2006 and 2007, linked to Law No. 3501, Law No. 3545, and Supreme Decree 29215, periods in which impacts ranged between 1.68 and 2.42 million hectares, all under the category of extreme-severe events.

The critical point of vulnerability in the socio-ecological system was identified in 2010, under the enforcement of Supreme Decree 429, when the largest event of the entire historical series was recorded, with a burned area of 4,243,522.92 hectares. This milestone was classified as a “compound hyper-severe event,” representing the maximum structural rupture detected in the study.

Subsequently, the implementation of regulations considered regressive, such as Law No. 1171 and Supreme Decree 3973 in 2019, coincided chronologically with fires that reached peaks exceeding 2.2 million hectares in September. These records were interpreted as catalysts for the expansion of the agricultural frontier due to the direct correlation between the enactment of such regulations and the immediate occurrence of extreme fire events.

In the final period analyzed (2022-2023), despite the enforcement of regulations referred to as “corrective or environmental,” such as Law No. 1525 and Supreme Decrees 4719 and 5074, a mutation in fire dynamics was verified. A temporal shift in severity was recorded toward the months of October and November, consolidating the category of “late extreme-severe events” with figures exceeding 1.8 million hectares. In sum, the use of statistical thresholds (P95) demonstrated that the management regime failed to generate a downward institutional rupture capable of returning the system to levels of natural variability. The recurrence of these events evidenced a long-term structural failure and a persistent disconnection between the environmental protection declared in the constitutional framework and the operational reality in Bolivian territory.

DISCUSSION

The identification of extreme thresholds and hyper-severe events in Bolivia during the period 2009-2023 reveals a fire dynamic that transcends natural variability, consolidating itself as a socio-ecological phenomenon in which institutional architecture is surpassed by the biophysical magnitude of disasters. When contrasting the findings with the climatology of extremes, the results confirm that the fire regime exhibits a “heavy-tailed” distribution, where specific episodes such as those of 2004 and 2010 fall within the 99th percentile (P_{99}), categorized as compound hyper-severe events (Coles, 2001; IPCC, 2019). This statistical distinction defines a breaking point where the magnitude of the fire exceeds the response capacity of both ecosystems and institutions, validating the usefulness of these thresholds for characterizing systemic risk in the country.

According to the compound events approach (Leonard et al., 2014), the classification of August 2010 as the “maximum hyper-severe event” demonstrates situations where the convergence of critical conditions surpasses the normal variability of the system. These episodes do not represent isolated fires but rather events of exceptional severity that, by situating themselves in the extreme tail of the empirical distribution, reveal limitations in institutional capacity to regulate land use. The persistence of the “extreme-severe” category recurrently until 2023 suggests that the current regulatory framework has not succeeded in reducing the magnitude of disasters, coinciding with warnings about the lack of effectiveness of protective laws in the face of economic incentives for land clearing (Cuéllar et al., 2012).

A critical finding lies in the identification of late extreme events during October and November 2023, which suggests a transition in the fire regime under the theory of structural discontinuities (Cleveland et al., 1990). While traditional fire ecology situates the seasonal peak in August and September, the emergence of events in the 95th percentile (P_{95}) at the end of the year indicates abrupt changes that extend the critical danger window. This temporal shift compromises the validity of historical averages as a reference for public management and challenges the calendars of authorized burns, demonstrating that prevention mechanisms are based on a climatic regime undergoing irreversible transformation (IPCC, 2022).

From the perspective of commons governance (Ostrom, 1990), the recurrence of extreme events in years such as 2019, 2022, and 2023 constitutes empirical evidence of failures in Bolivia’s institutional architecture. The correlation observed in 2019, when specific regulations preceded large-scale fires, confirms that certain policies act as catalysts for the expansion of the agricultural frontier rather than as control mechanisms. The existence of events based on large burned areas without an equivalent increase in fire hotspots reinforces the notion of a transition toward fires of greater spread and lower controllability, linked to structural weaknesses in territorial control (Pivello et al., 2021).

Finally, the absence of a linear annual trend according to the Mann-Kendall test and Sen’s slope estimator does not imply stability, but rather a system dominated by volatility and the episodic occurrence of large-scale fires (Bowman et al., 2009). The evidence suggests that hyper-severity has consolidated itself as a systemic characteristic of the contemporary Bolivian landscape. Therefore, the critical evaluation of public policies during the period 2009-2024 indicates that the legal framework has failed to mitigate extremes,

obliging a rethinking of fire governance from a preventive approach that acknowledges these new realities of thermal risk and seasonal ruptures.

CONCLUSIONS

The application of robust statistical criteria allows hyper-severity to be formally defined as the new normal in Bolivia's fire regime. The use of the 95th (P_{95}) and 99th (P_{99}) percentiles establishes an operational definition that transcends historical averages, identifying that events such as those of 2004 and 2010 are not isolated anomalies but indicators of a socio-ecological system that has reached critical levels of vulnerability. This characterization of "heavy tails" in the fire distribution demonstrates that the magnitude of current disasters recurrently collapses institutional response capacity, consolidating a state of systemic risk where exceptional severity is an intrinsic feature of the contemporary landscape.

Scientific evidence confirms a structural rupture in fire seasonality, manifested through an extension of the critical window into the last quarter of the year. The identification of late extreme events in October and November 2023 invalidates administrative burn calendars and traditional control parameters, suggesting that biophysical cycles are undergoing profound transformations. This temporal shift, combined with the emergence of thermal anomalies in transitional months such as February and March, demands that public management abandon approaches based on historical stability and adopt dynamic monitoring mechanisms capable of responding to a fire regime in constant mutation.

The recurrence of episodes exceeding critical thresholds during the period 2009-2023 functions as empirical evidence of structural failure in environmental governance. The persistence of hyper-severity under the post-constitutional regulatory framework reveals that institutional architecture lacks effective monitoring mechanisms and credible sanctions to contain fire expansion. On the contrary, the correlation observed between specific regulations and peaks in burned area in years such as 2019 suggests that the legal framework has, at times, acted as a catalyst for the expansion of the agricultural frontier, prioritizing economic incentives over the ecological security of common goods.

The transition toward rapidly spreading and high-intensity fires, evidenced by the disconnection between affected area and hotspot density, reflects a degradation of the landscape that facilitates uncontrolled fire expansion. This gap between surface magnitude and operational suppression capacity underscores the insufficiency of current reactive policies. It is concluded that the effectiveness of fire management in Bolivia depends on an immediate restructuring of public policies, which must shift from emergency response toward comprehensive territorial governance that eliminates regressive regulatory incentives and strengthens preventive territorial control.

RECOMMENDATIONS

It is imperative to move from a reactive management model toward a comprehensive landscape governance framework that recognizes hyper-severity as a systemic condition. To this end, the immediate updating of burn calendars and prohibition periods is recommended, replacing historical averages with dynamic monitoring systems that account

for the extension of the critical window detected in October and November. This administrative flexibility must be supported by an early warning system based on the 95th (P_{95}) and 99th (P_{99}) percentiles, enabling the activation of international emergency protocols before the biophysical magnitude of fire exceeds national operational response capacity.

From a regulatory perspective, it is essential to conduct a critical review and possible repeal of decrees and laws considered regressive, which incentivize land-use change in vulnerable ecosystems. Instead, the implementation of commons governance mechanisms is proposed, incorporating credible sanctions and effective territorial monitoring, aligning secondary legislation with the environmental protection principles of the Constitution. Public policy must prioritize the elimination of economic incentives for land clearing in areas with high recurrence of hyper-severe events, strengthening state presence in territorial control to prevent isolated ignitions from escalating into large-scale disasters.

It is further recommended to strengthen the technical capacity of institutions responsible for fire management through the adoption of robust statistical criteria for performance evaluation. The use of extreme climatology should be institutionalized as an auditing tool for public policies, allowing the effectiveness of interventions to be measured not only by the number of fire hotspots but also by the effective reduction of burned area in heavy-tail events. This restructuring should promote community-based fire management and post-fire ecological restoration, ensuring that ecosystem resilience and socio-ecological security become the central axis of the new institutional architecture of fire governance in Bolivia.

REFERENCES

- Anívarro, R., Chuvieco, E., & Vilar, L. (2019). Análisis de umbrales críticos para la gestión del fuego en ecosistemas tropicales. [Analysis of critical thresholds for fire management in tropical ecosystems]. *Revista de Ecología Aplicada*, 14(2), 115-128.
- Bai, J., & Perron, P. (2003). Computation and analysis of multiple structural change models. *Journal of Applied Econometrics*, 18(1), 1-22. <https://doi.org/10.1002/jae.659>
- Bowman, D. M., Balch, J. K., Artaxo, P., Bond, W. J., Carlson, J. M., Cochrane, M. A., D'Antonio, C. M., DeFries, R. S., Doyle, J. C., Harrison, S. P., Johnston, F. H., Keeley, J. E., Krawchuk, M. A., Kull, C. A., Marston, J. B., Moritz, M. A., Prentice, I. C., Roos, C. I., Scott, A. C., ... Pyne, S. J. (2009). Fire in the Earth system. *Science*, 324(5926), 481-484. <https://doi.org/10.1126/science.1163886>
- Cleveland, R. B., Cleveland, W. S., McRae, J. E., & Terpenning, I. (1990). STL: A seasonal-trend decomposition procedure based on loess. *Journal of Official Statistics*, 6(1), 3-73
- Coles, S. (2001). *An introduction to statistical modeling of extreme values*. Springer-Verlag.
- Constitución Política del Estado. (2009) [Political Constitution of the State]. (2009). *Gaceta Oficial de Bolivia*. 7 de febrero de 2009.
- European Commission, Directorate-General for Communication. (2015). *The EU explained: Climate action*. Publications Office of the European Union. <https://data.europa.eu/doi/10.2775/543163>
- Cuellar, S., Vides, R., & Villegas, P. (2012). Evaluación de la gestión del fuego y políticas públicas en Bolivia. [Evaluation of fire management and public policies in Bolivia]. Fundación Amigos de la Naturaleza (FAN).

- Devisscher, T., Malhi, Y., Rojas, M., & Boyd, E. (2016). Understanding the fire regime and its socio-ecological context in the Chiquitania forest of Bolivia. *Ecology and Society*, 21(3), 9. <https://doi.org/10.5751/ES-08631-210309>
- FAO. (2020). *Directrices para la gestión del fuego en áreas protegidas y bosques tropicales. Guidelines for fire management in protected areas and tropical forests*. Organización de las Naciones Unidas para la Alimentación y la Agricultura. <https://www.fao.org>
- Helsel, D. R., & Hirsch, R. M. (2002). *Statistical methods in water resources*. U.S. Geological Survey. <https://doi.org/10.3133/twri04A3>
- Instituto Nacional de Pesquisas Espaciais. (2024). *Monitoramento dos focos ativos por países: Queimadas*. Ministério da Ciência, Tecnologia e Inovações. https://terrabrasilis.dpi.inpe.br/queimadas/portal/estatistica/estatisticas_paises
- IPCC. (2012). *Managing the risks of extreme events and disasters to advance climate change adaptation (SREX)*. Cambridge University Press. <https://www.ipcc.ch>
- IPCC. (2019). *Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. Intergovernmental Panel on Climate Change. <https://www.ipcc.ch>
- IPCC. (2022). *Climate change 2022: Mitigation of climate change*. Cambridge University Press. <https://www.ipcc.ch>
- Leonard, M., Westra, S., Phatak, A., Lambert, M., van den Hurk, B., McInnes, K., Risbey, J., Schuster, S., Jakob, D., & Stafford-Smith, M. (2014). A compound event framework for understanding extreme impacts. *Wiley Interdisciplinary Reviews: Climate Change*, 5(1), 113-128. <https://doi.org/10.1002/wcc.252>
- Müller, R., Müller, D., Schierhorn, F., & Gerold, G. (2013). Spatiotemporal modeling of the expansion of medium- and large-scale agriculture in the Bolivian lowlands. *Remote Sensing*, 5(3), 1442-1467. <https://doi.org/10.3390/rs5031442>
- Ostrom, E. (1990). *Governing the commons: The evolution of institutions for collective action*. Cambridge University Press. <https://doi.org/10.1017/CBO9780511807765>
- Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science*, 325(5939), 419-422. <https://doi.org/10.1126/science.1172133>
- Pivello, V. R., Vieira, I., Christianini, A. V., Ribeiro, D. B., Menezes, L. S., Berlinck, C. N., Melo, F. P., Marengo, J. A., Tornquist, C. G., Overbeck, G. E., Ferreira, J. N., Schmidt, I. B., Mistry, J., & Loyola, R. (2021). Understanding Brazil's catastrophic fires: Causes, consequences and policy needed to prevent future tragedies. *Perspectives in Ecology and Conservation*, 19(3), 233-255. <https://doi.org/10.1016/j.pecon.2021.06.005>