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Fire asymmetries across global borders reveal distinct ecological governance and cooperation priorities

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Abstract

International borders divide governance systems but often cut across continuous ecosystems, creating potential mismatches in fire management. We analyze 277 terrestrial international border pairs using a 21-year satellite fire record and integrate fire burden, relative cross-border asymmetry, ecological value, institutional challenge and cooperation challenge. Border fire burden broadly reproduces global fire geography, with the highest activity concentrated in major fire-prone regions, but our analysis shows that management implications differ markedly among borders. Among 128 active-fire pairs, fire burden and proportional asymmetry are weakly negatively associated and identify partly distinct priorities. Ecological value further reshapes priority geographies, while institutional and cooperation constraints define different governance contexts. Multivariate analysis separates these borders into operational profiles with contrasting management needs. Here, we show that transboundary fire priority cannot be inferred from fire activity alone but emerges from distinct combinations of fire, ecological and governance conditions, requiring border-specific approaches to monitoring, conservation and cooperation.

Introduction

Vegetation fires are fundamental ecological processes shaping ecosystems worldwide, yet they also represent a growing socio-ecological challenge for societies seeking to manage their frequency, intensity, and impacts [1,2]. Intensifying human pressures, land-use transformation, climate extremes, and expanding exposure in fire-prone landscapes are altering fire regimes, with consequences for ecosystem integrity, human health, and disaster risk, thereby making wildfire an important sustainable development challenge [3–5]. Fire management must simultaneously protect natural resources, reduce potential harms to public health such as smoke exposure, limit downstream pollution, and lower risks to populations in wildland-urban interfaces [6–8]. Typically, fire governance remains largely organized through national, subnational, or sectoral institutions, with management decisions implemented by agencies and landowners operating within legal and administrative boundaries, while large and extreme fire events can cross municipal, provincial, protected-area, and national jurisdictions, creating multi-agency coordination problems [9,10]. This produces a fundamental mismatch: the effects of fires are spatially continuous and mobile, whereas governance is politically bounded.

This mismatch is especially important in borderlands. Political borders, whether internal or international, rarely coincide with ecological boundaries or the distribution of flammable vegetation. Many border regions cut across biophysically continuous mountain ranges, forests, savannas, grasslands, wetlands, and drylands, where species, habitats, ecological processes, and ecosystem services extend across both sides of a boundary. The ecological continuity of these shared landscapes makes them important for cooperative conservation and management [11–13]. A global-scale quantification showed that more than half of global terrestrial bird, mammal, and amphibian species, and roughly one-fifth of threatened species, have transboundary ranges [14]. Under RCP 8.5 projections for 2070, approximately 35% of

mammals and 29% of birds are expected to cross international boundaries to follow their climatic niche [15].

At the same time, borders can coincide with sharp institutional, socioeconomic, and land-use discontinuities within otherwise connected landscapes [16]. Adjacent areas may share similar climate, topography, and vegetation, yet differ abruptly in land tenure, agricultural burning practices, forest management, infrastructure, protected-area enforcement, suppression capacity, governance quality, and cultural attitudes toward fire [17]. Recent global work has also shown that biodiversity protection in borderlands is related to governance and bilateral cooperation, underscoring the value of treating transboundary regions as analytical units [18]. Fire, however, has not been assessed globally in this bilateral border-pair framework. Along the U.S.–Mexico frontier, comparable climatic zones display contrasting fire frequencies and intensities associated with differences in land use and suppression policy [19]. In Europe, cross-border fire-spread modeling has shown that fire fronts can propagate across national boundaries, requiring harmonized risk planning [20]. Wildfires also transmit impacts across borders through flames, smoke, lofted firebrands, erosion, pollution, and biodiversity loss [21–25]. Borderlands therefore should not be viewed merely as political margins or administrative divides, but as shared ecological systems where high biodiversity and conservation value intersect with institutional, land-use, and management discontinuities that can contribute to asymmetric fire patterns and other transboundary environmental risks.

International cooperation on wildfire management has gained visibility, but it remains uneven. Bilateral and regional frameworks show both the potential and limits of coordinated governance. Spain and Portugal, for instance, maintain a civil-protection protocol that allows rapid initial attack within a 25 km strip on either side of the border [26]. In Southeast Asia, the ASEAN Agreement on Transboundary Haze Pollution provides a legally binding framework to reduce smoke from peat and forest fires, although compliance and enforcement challenges persist [27]. Despite such examples, most scientific assessments and policy mechanisms remain nationally framed, often matching administrative priorities rather than ecological continuities. Existing global fire studies have mapped burned area, fire frequency, emissions, seasonality, and climatic or human correlates, but they rarely treat international borders as analytical units or ask whether overall fire burden and bilateral fire asymmetry identify the same places. High fire activity alone therefore cannot define transboundary sustainability priority: fire burden, cross-border asymmetry, ecological value, institutional capacity, and cooperation constraints may identify different border problems and require different policy responses.

This study addresses that gap by developing a global border-fire framework fire burden and cross-border asymmetry with ecological value, institutional capacity, and cooperation potential. The framework connects three dimensions of the Sustainable Development Goals: SDG 15, because fire affects terrestrial ecosystems, biodiversity, forests, and land degradation; SDG 16, because fire management depends on institutional capacity, governance effectiveness, and rule of law; and SDG 17, because transboundary fire management requires cooperation among neighboring countries and regional

institutions [28–30]. Although the SDGs are largely implemented and monitored through national frameworks, many of the ecological and governance processes they address are transboundary. Border regions may therefore become a spatial blind spot, where shared ecosystems and cross-border differences are obscured by country-based assessments. Using integrated global fire, ecological, climatic, socioeconomic, and governance data, we assess fire patterns and asymmetries along terrestrial international borders and evaluate how fire burden, ecological value, institutional challenge, and cooperation challenge converge or diverge. By treating border pairs as shared ecological and governance units, this study provides a framework for identifying distinct transboundary fire priorities and management needs.

Results

Fire burden and cross-border asymmetry identify distinct border priorities

Fire burden was highly uneven across terrestrial international border pairs. Of the 277 analyzed, 149 had negligible or very low mean fire density (≤ 0.1 fire records km^{-2} over the 21-year study period), while 128 were classified as active-fire pairs. We used this threshold to separate border pairs with sufficient fire activity for meaningful asymmetry analysis from those where proportional differences can be inflated by near-zero fire occurrence. Across all pairs, mean fire density was strongly right-skewed (Supplementary Fig. 1), with the highest values concentrated in tropical regions of Africa and Southeast Asia, reaching 3.53 fire records km^{-2} over the 21-year study period.

Fire asymmetry captured a related but distinct dimension of transboundary fire activity. Although fire density was often relatively similar between the two sides of each border pair, absolute fire gaps tended to be larger where total fire activity was high (Supplementary Fig. 2). This relationship partly reflects the arithmetic structure of the metric, since larger fire densities allow larger absolute differences. Nevertheless, absolute gaps remain useful for identifying borders where unequal fire density may generate substantial management demands. Relative gaps, by contrast, identify proportional imbalance between neighboring sides, but they are most meaningful after excluding negligible fire contexts. Several border pairs with very low fire density, such as Finland–Norway, Algeria–Morocco, and Belgium–Germany, had relative gaps close to one, but the absolute differences were minimal. Among active-fire border pairs, the median relative fire gap was 0.258, indicating that the higher fire side typically accounted for a substantially larger share of pair-level fire density than the lower fire side (Supplementary Table 1). However, fire burden and proportional fire asymmetry did not increase together. Across active-fire pairs, mean fire burden and relative fire gap were weakly but significantly negatively correlated (Spearman's $\rho = -0.263$, $P = 0.0027$; Supplementary Fig. 3), indicating that the most fire-prone borders were generally not the most proportionally asymmetric.

We then classified fire burden and relative cross-border fire gap into terciles to identify borders where high overall fire activity and strong proportional imbalance coincide. The largest class was high fire burden with medium relative fire gap (22 pairs, 17.2% of active-fire pairs), followed by low fire burden with high relative fire gap (21 pairs, 16.4%). Nine border pairs (7%) fell into the combined high burden and high relative gap class and were the following (first country in each pair is the higher fire density side): Mozambique–Swaziland, Tanzania–Rwanda, Cambodia–Thailand, Guinea–Côte d'Ivoire, Mozambique–Zambia, Mozambique–Malawi, Burkina Faso–Côte d'Ivoire, South Africa–Swaziland, and Benin–Niger (Fig. 1). Permutation-based overlap tests supported this result. The observed overlap of the top tercile was lower than expected under random reassignment, although marginally so (9 observed vs 14.45 expected; two-sided empirical P = 0.0501), and the top-quartile overlap was substantially lower than expected (2 observed vs 8 expected; two-sided empirical P = 0.0068; Supplementary Table 2). These results show that high fire burden and high proportional asymmetry identify partly different sets of border pairs.

Fire burden and fire asymmetry have different correlates

Globally, fire burden was structured by broad environmental, vegetation, and institutional gradients (Fig. 2, left). Fire density was higher in warmer, low latitude, more productive, and shrub-rich border contexts, and lower in more rugged and institutionally stronger contexts, including border pairs with higher HDI, government effectiveness, rule of law, and political stability. These associations were consistent across OLS and Gamma model specifications (Supplementary Table 3), indicating that fire burden covaries with a broad set of climatic, fuel, land-use, and governance conditions rather than with a single environmental control [2,31–34].

Relative cross-border fire gap showed a different and substantially less predictable structure (Fig. 2, center). Among active-fire pairs, lower precipitation showed the strongest nominal association with larger relative fire gaps, both when controlling for mean fire burden and in the sensitivity model without this control. However, neither association remained significant after FDR adjustment, and no predictor retained significance in either active-fire specification (Supplementary Table 4). Models including all border pairs produced several significant associations after FDR correction, but some differed in direction from the active-fire results, highlighting the sensitivity of relative gap models to low fire contexts. We therefore find limited evidence for broad, globally consistent correlates of proportional cross-border fire asymmetry. Ecological value variables similarly showed no robust association among active-fire pairs; habitat quality for terrestrial vertebrates was nominally associated with lower relative fire gap in individual models but did not remain significant after multiple testing correction. Overall, relative fire gaps appear more locally structured and less predictable than fire burden.

Within-pair models provided exploratory evidence of side-level contrasts across the same border (Fig. 2, right). In active-fire pairs, the side with higher road density, agricultural cover, rule of law, and political stability tended to have lower fire density. The latter three associations were nominally significant in both

all-pair and active-fire sensitivity models, whereas road density was significant only among active-fire pairs. However, no factor remained significant after FDR adjustment (Supplementary Table 5), so these results should be interpreted cautiously and not as causal effects. The direction of the associations nevertheless suggests that, within the same border pair, more agricultural, more accessible, and institutionally stronger sides often burn less, consistent with anthropogenic mechanisms such as land-use intensification, suppression capacity, fire regulation, or reduced fuel continuity [33–35].

The Goldstein cooperation proxy did not reliably predict whether neighboring countries share similar or divergent fire conditions. However, constructive bilateral relations remain important, in particular once a transboundary fire issue has been identified: to tackle the problem, coordinated fire management will rely on institutional capacity, communication, trust, and cross-border cooperation [35,36].

Ecological value reframes transboundary fire priority

Ecological value provided a second filter on border fire priority by combining conservation relevance with fire exposure and fire asymmetry. Of the 93 border pairs falling in the high ecological value tercile, 57 occurred in active-fire borderlands. Among these, 16 fell in the low fire burden tercile, 25 in the medium fire burden tercile, and 16 in the high fire burden tercile (Fig. 3a). The fire asymmetry dimension further refined this prioritization. Among the 57 active-fire pairs in the high ecological value tercile, 20 fell in the low relative gap tercile, 19 in the medium relative gap tercile, and 18 in the high relative gap tercile (Fig. 3b). These latter high-high borders were not necessarily the same as the highest fire burden borders. A selective subset of five pairs was simultaneously classified as high ecological value, high fire burden, and high relative fire gap: Cambodia–Thailand, Tanzania–Rwanda, Mozambique–Swaziland, South Africa–Swaziland, and Guinea–Côte d'Ivoire.

Together, the two maps show that ecological fire priority is multidimensional. This interpretation is supported by the weak correlations and limited high-priority overlaps among ecological value, fire burden, and relative fire gap, indicating that these dimensions do not form a single shared hotspot geography (Supplementary Fig. 3; Supplementary Table 2).

Institutional and cooperation constraints define different governance problems

The ecological priority maps identify where fire matters most for conservation, but they do not indicate whether coordinated fire action is likely to be easy to implement. Using the same tercile division method, we added two different governance classifications: institutional challenge (related to SDG 16) and cooperation challenge (related to SDG 17). The combination of high fire burden and high institutional challenge was found in 17 cases, all in West, Central and East African borders such as South Sudan–Uganda, DRC–Zambia, DRC–Angola, Guinea–Guinea-Bissau, and DRC–South Sudan (Fig. 4a). None of these pairs overlapped with the 18 cases in the high relative fire gap and high cooperation challenge

class (Fig. 4b), which in addition to some African borders such as DRC–Uganda, DRC–Rwanda, Mozambique–Malawi, and South Africa–Swaziland, also included Iran–Iraq, Turkey–Syria, Azerbaijan–Armenia, France–Spain, and Russia–Poland.

Integrating fire, ecological, and governance dimensions into management pathways

Because the five framework dimensions were only partly coupled (full correlation matrix in Supplementary Fig. 3), k-means clustering was applied to the 128 active-fire border pairs to define data-driven fire management profiles based on five standardized variables: log1p-transformed mean fire burden, relative fire gap, ecological value, institutional challenge, and cooperation challenge (Fig. 5). The maximum silhouette criterion identified seven clusters, although the silhouette value was relatively low, indicating gradual transitions among profiles rather than sharply separated natural classes (Supplementary Table 6). PCA diagnostics further showed that the first two components explained 58.5% of the standardized five-variable variation, with PC1 representing mainly high fire burden and institutional challenge gradients while PC2 was high relative fire gap and cooperation challenge. PC3 was mainly an ecological value axis, bringing the cumulative explained variance to 77.8% (Supplementary Fig. 4; Supplementary Table 7). The PCA biplot is therefore used only as a diagnostic visualization, while clustering was performed in the full standardized five-variable space rather than in the reduced PCA space.

The seven clusters provide an operational segmentation of this continuous five-dimensional priority space. C01 included 23 pairs with high fire burden and high institutional and cooperation challenges, including Mozambique–Tanzania, South Sudan–Uganda, DRC–Zambia, and Nigeria–Cameroon. We interpret this cluster as a coordinated fire burden reduction profile, where prevention, preparedness, and response are likely to depend on institutional capacity and cross-border coordination. C02 included 16 pairs with high relative fire gap and high institutional and cooperation challenges, including Turkey–Syria and Turkey–Iraq borders, DRC–Rwanda, Azerbaijan–Armenia, Iraq–Iran, and North Korea–South Korea. This cluster represents an asymmetric risk diplomacy profile, where one-sided fire regimes require shared diagnosis, data exchange, and negotiated coordination before intervention. C03 included 26 high fire burden pairs with lower cooperation challenge scores, such as DRC–Angola, Guinea–Côte d'Ivoire, Mozambique–Swaziland, Cambodia–Thailand, Tanzania–Rwanda, and Benin–Niger, and represents an operational fire reduction profile focused on lowering overall fire pressure. C04 and C06 were primarily defined by ecological value. C04 included 26 ecologically valuable pairs with moderate fire and governance concerns, such as South Africa–Swaziland, Burma–Thailand, South Africa–Mozambique, India–Burma, and Liberia–Sierra Leone, while C06 included 12 ecologically valuable pairs with low relative gap and lower institutional or cooperation challenge, including Vietnam–Cambodia, Cambodia–Laos, Laos–Vietnam, and Thailand–Laos. These two clusters indicate conservation-fire integration and ecological stewardship profiles, where fire planning should be linked to habitat protection, connectivity, protected-area management, and preventive monitoring. C05 included nine low burden but high

asymmetry pairs, representing a proportional mismatch watchlist where strong relative differences should be monitored but not overinterpreted as very high fire exposure. Finally, C07 included 16 active fire pairs with comparatively lower combined priority across the five variables and is best interpreted as a routine fire monitoring profile. Full cluster membership and variable scores are provided in Supplementary Data 1.

Discussion

largely reproduces the major fire-prone regions identified by global satellite observations, with the highest fire burdens concentrated in tropical Africa, Southeast Asia, and South America. (https://firms.modaps.eosdis.nasa.gov/, accessed June 2026). However, the management implications of these patterns are not reducible to fire activity alone. Fire burden, proportional asymmetry, ecological value, institutional challenge, and cooperation challenge were only partly coupled, meaning that borders embedded within similarly fire-prone regions can present different management problems. This extends recent global work showing that conservation outcomes in borderlands depend on governance and bilateral cooperation [18] by demonstrating that fire adds an additional asymmetric dimension that becomes visible when neighboring countries are analyzed as border pairs rather than independently.

This distinction is particularly important for conservation. High fire density and high cross-border mismatch represent different forms of exposure, and neither one necessarily coincides with high ecological value. Conservation priority is generally defined by combining biological value with threat, exposure, or vulnerability [37–39]; in borderlands, contrasting fire patterns across otherwise connected ecosystems may therefore create additional challenges for habitat connectivity and coordinated management. We interpret the high-high classes in Fig. 3 as screening categories for identifying where fire management and transboundary conservation planning may need to be considered together. The limited overlap among the five framework dimensions further shows that institutional and cooperation constraints define different governance problems. DRC–Uganda and DRC–Rwanda, for example, combine high ecological value with high relative fire asymmetry and strong institutional and cooperation challenges. These borders lie within the broader Greater Virunga regional context, where transboundary conservation has long required coordination among DRC, Rwanda, and Uganda, despite sustained conflict, displacement, ranger security concerns, and resource extraction [40]. South Sudan–Uganda represents a different configuration, combining high fire burden and ecological value with institutional and cooperation challenges but without a dominant asymmetry signal, pointing instead toward the need for coordinated management of overall fire pressure [41]. The Kurdistan region, in particular the Turkey–Iraq border, in contrast, is not one of the strongest ecological value cases, but it is a clear high relative gap and high cooperation challenge case, consistent with the practical difficulty of fire response in borderlands affected by long conflicts [42]. These examples illustrate why similar levels of fire activity can imply different management needs depending on ecological and governance context.

The framework should therefore be interpreted as a flexible global screening tool and not a prescriptive ranking. Socio-political borders rarely coincide with ecological boundaries, yet they can divide ownership, regulation, enforcement, monitoring, and management responsibility, with consequences for conservation and environmental governance [17]. Cross-boundary collaboration is therefore important, but its feasibility and benefits vary among regions and should be assessed explicitly [12]. Supplementary Data 1 is intended to support such context-specific use by providing the five framework variables, their 0–1 ranks, active-fire status according to the threshold used in this study, clustering membership and management interpretation for all border pairs. This flexibility is important because fire is not uniformly harmful: it is a fundamental ecological process shaping vegetation structure, carbon cycling, and biodiversity [1,2], and our global framework does not distinguish fire-sensitive habitats from fire-adapted or fire-dependent ecosystems. Likewise, the 149 negligible or very low fire pairs were less central to the specific objectives of this study, but this does not imply that they are unimportant for transboundary cooperation. Fire may still warrant monitoring in some of these regions, while cooperation may remain essential for biodiversity conservation, invasive-species management, water resources, protected-area connectivity, land use, migration, or other shared environmental concerns. The value of the framework and the output data is therefore to help international organizations, regional bodies, and neighboring countries distinguish different border problems and match them to appropriate forms of response.

Several limitations follow from the global design. First, international boundary datasets are cartographic and political representations, not necessarily survey-grade descriptions of de facto control. As such, disputed, generalized, riverine, or poorly demarcated borders may introduce positional uncertainty. Second, the 5 km buffer was selected to characterize the immediate border interface and limit dilution by broader within-country conditions. A wider buffer would reduce sensitivity to boundary position error and capture broader landscape fire processes, but it would also mix borderland signals with interior gradients and weaken the interpretation of borders as potential ecological discontinuities. Third, all input layers, including the fire product, ecological indicators, environmental variables, and socio-economic or governance datasets, come from remote sensing products, global models, or aggregated databases, each containing uncertainty and bias that propagates into subsequent analyses. Finally, border polygons are fixed analytical units of unequal size, so long borders may average over localized hotspots, while river or lake borders may contain limited terrestrial area relevant to fire. These choices are necessary for global consistency, but the results should guide prioritization and hypothesis generation rather than replace local ecological assessment, field validation, or bilateral planning. Countries and regional organizations should identify which portions of a border correspond to the patterns summarized here, and where finer-scale mapping, stakeholder consultation, or joint management planning is needed.

More broadly, our results highlight a spatial gap in sustainability governance. Although the Sustainable Development Goals are largely implemented and monitored through national frameworks, fire, biodiversity, water, pollution, and other ecological processes routinely cross political boundaries. Border regions may therefore be poorly represented when neighboring countries are assessed independently. Future post-2030 sustainability frameworks should more explicitly recognize border regions as shared

social-ecological systems through transboundary indicators, joint monitoring, and bilateral or regional reporting. Such approaches could better connect biodiversity conservation, institutional capacity, and international cooperation across the objectives represented by SDGs 15, 16, and 17.

Methods

Study design and analytical units.

We developed a global screening framework to evaluate international borders as coupled ecological and governance interfaces for fire management. The analytical units were adjacent polygons built from terrestrial international border lines (geoBoundaries dataset [43]). We delineated a 5 km buffer on each side of terrestrial country boundaries, excluding disputed borders, small enclaves, entirely non-terrestrial units, and border units without burnable land cover. The 5 km buffer was chosen to focus on the immediate border interface while retaining a globally consistent and computationally tractable design. The final dataset comprised 277 terrestrial international border pairs. The analysis proceeded in five steps: first, we quantified fire burden and cross-border fire asymmetry for each border pair; second, we modeled broad correlates of fire burden and relative fire gap; third, we constructed ecological, institutional, and cooperation indices; fourth, we evaluated multidimensional priority structure based on these five indices; and finally, we compiled all original variables, derived indices, classifications, and cluster membership into a reproducible dataset.

Fire records and covariates

Fire records were derived from a 21-year satellite fire dataset, GlobFire [44], which is based on MODIS/NASA fire products [45]. For each border side, we calculated fire density as the number of fire records divided by burnable area over the full study period. Burnable area was defined using vegetation and agricultural land cover classes from GLC-2000 [46], excluding urban areas, bare ground, water, and permanent snow or ice. Each border pair was oriented so that B1 represented the higher fire density side and B2 the lower fire density side (Supplementary Data 1 and Legend for Supplementary Data 1).

We compiled environmental, ecological, socioeconomic, institutional, and cooperation variables for each border unit. Climatic variables included mean temperature and precipitation from WorldClim v2.1 [47], potential evapotranspiration and aridity index from CGIAR-CSI [48], and absolute latitude from border centroids. Topographic variables included elevation and the vector ruggedness measure from EarthEnv products based on SRTM [49], and vegetation heterogeneity was represented by Shannon diversity of Enhanced Vegetation Index [50]. Land cover variables extracted from GLC-2000 measured proportional tree, shrub, grassland, and agricultural cover. Human pressure variables included population density from GPWv4 [51], night-time lights from NOAA (https://sos.noaa.gov/catalog/datasets/nighttime-lights/, accessed June 2026), Human Footprint [52], road density from GRIP4 [53], agricultural GDP [54], GDP per capita and HDI from Kummu and colleagues [55]. Institutional variables were government effectiveness,

rule of law, and political stability from the World Governance Indicators [56]. Bilateral cooperation context was represented using Goldstein scores derived from ICEWS event data and the CAMEO coding framework [57–59]. Conservation variables included coverage by Biodiversity Hotspots [38], Key Biodiversity Areas [60,61], protected areas from WDPA [62], and habitat quality for terrestrial vertebrates from Wu et al. [63].

Fire burden and cross-border asymmetry

For each border pair, we calculated mean fire burden as the average fire density of the two sides and absolute fire gap as the difference between the higher fire and lower fire sides. Relative fire gap was calculated as the absolute gap divided by the sum of both side fire densities plus a small positive constant (ε) used to avoid division by zero (see Legend for Supplementary Data 1). Border pairs with mean fire density ≤ 0.1 over the 21-year study period were classified as lower concern pairs based on the distribution of mean fire burden (Supplementary Fig. 1). The remaining 128 pairs were treated as active-fire pairs. Relative fire gap analyses were interpreted primarily among active-fire pairs because proportional differences can be inflated when fire activity is close to zero. For mapping and priority screening, fire burden and relative fire gap were divided into terciles among active-fire pairs only, while absolute fire gap was retained as an additional measure of asymmetry.

Statistical models

We modeled fire burden and fire asymmetry separately. For fire burden, the main model was an OLS regression with HC3 robust standard errors fitted to log1p-transformed mean fire density across all border pairs. Sensitivity models included the same OLS-HC3 model for active-fire pairs only, a Gamma generalized linear model with log-link for positive fire pairs, and a Gamma log-link model for active-fire pairs. Predictors were standardized and fitted one at a time. For relative fire gap, the main model used logit-transformed relative gap among active-fire pairs, with log1p-transformed mean fire burden included as a control. Sensitivity models removed the mean fire control and repeated the same model across all pairs. To evaluate side-level differences within the same border pair, we fitted within-pair OLS models to log1p-transformed side fire density. Pair fixed effects were implemented by demeaning both response and predictor variables within each pair, and standard errors were clustered by border pair. Because predictors were fitted separately across multiple variables, Benjamini–Hochberg false-discovery-rate (FDR) [64] adjusted P values were calculated across predictors within each model specification. We report both unadjusted P values and FDR-adjusted q values and interpret associations that did not survive FDR correction as nominal or exploratory.

Ecological, institutional, and cooperation indices

Ecological value was summarized with a rank-based index. Biodiversity Hotspot coverage, KBA coverage, and protected-area coverage of all border pairs were rank-transformed to a 0–1 scale and averaged into a Coverage Index. Habitat quality for terrestrial vertebrates, having a different values range system, was ranked separately. The final ecological index was calculated as 0.5 × Coverage Index + 0.5 × Vertebrate Value Index, giving equal weight to conservation-designation coverage and vertebrate habitat value.

Institutional challenge was calculated from government effectiveness, rule of law, and political stability. Each variable was ranked across all border sides, then averaged into a side-level institutional capacity index. For each pair, we used the lower of the two sides capacity values to represent the weakest side constraint, and calculated institutional challenge as 1 minus this minimum capacity. Cooperation challenge was based on the minimum Goldstein score between the two sides. We ranked this cooperation potential value using all border pairs and calculated cooperation challenge as 1 minus the normalized rank. We produced bivariate maps combining ecological value, institutional challenge, or cooperation challenge with fire burden or relative fire gap using tercile classes. Fire burden and relative fire gap thresholds were defined among active-fire pairs, whereas ecological value, institutional challenge, and cooperation challenge retained their global all-pair ranking. Specific formulas for these indices are listed in Legend for Supplementary Data 1.

Multidimensional priority analyses

To evaluate whether the five framework dimensions formed a single priority gradient or identified partly distinct priorities, we computed pairwise Spearman rank correlations because several variables were skewed, bounded, or rank-based. Correlations were calculated for active-fire pairs, with an all-pair matrix reported as broader context. We also used permutation-based overlap tests to compare observed overlaps among high-priority classes with null expectations. High-priority groups were defined using top-tercile, top-quartile, and top-decile thresholds. Observed overlaps were compared with null distributions from 10,000 random permutations that preserved the number of high-priority pairs in each dimension while breaking associations among dimensions. Finally, we used k-means clustering to integrate the five framework variables into fire management profiles: log1p-transformed mean fire burden, relative fire gap, ecological value, institutional challenge, and cooperation challenge. Clustering was applied only to active-fire pairs after standardization with StandardScaler, while the 149 negligible fire pairs were retained as a separate low concern class and included in the final map. Candidate solutions from k = 2 to k = 8 were compared using silhouette score, Calinski-Harabasz score, Davies-Bouldin index, and inertia, and the final solution was selected by the maximum silhouette criterion [65–67]. We also applied PCA as a diagnostic visualization of multivariate structure, while clustering was performed in the full standardized five-variable space.

Software and reproducibility

Geospatial processing and mapping were performed in Google Earth Engine [68] and QGIS 3.34 (http://www.qgis.org/, accessed June 2026), while statistical analyses were implemented in Python using pandas, NumPy, SciPy, statsmodels, scikit-learn, and matplotlib [69,70].

Data availability

All source datasets used in this study are publicly available from the repositories cited in the Methods. As a final deliverable, Supplementary Data 1 provides the original values of the five framework variables, derived ranks, active fire status, and clustering membership for all border pairs.

Declarations

Competing Interest Statement: No competing interests to declare.

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Figures

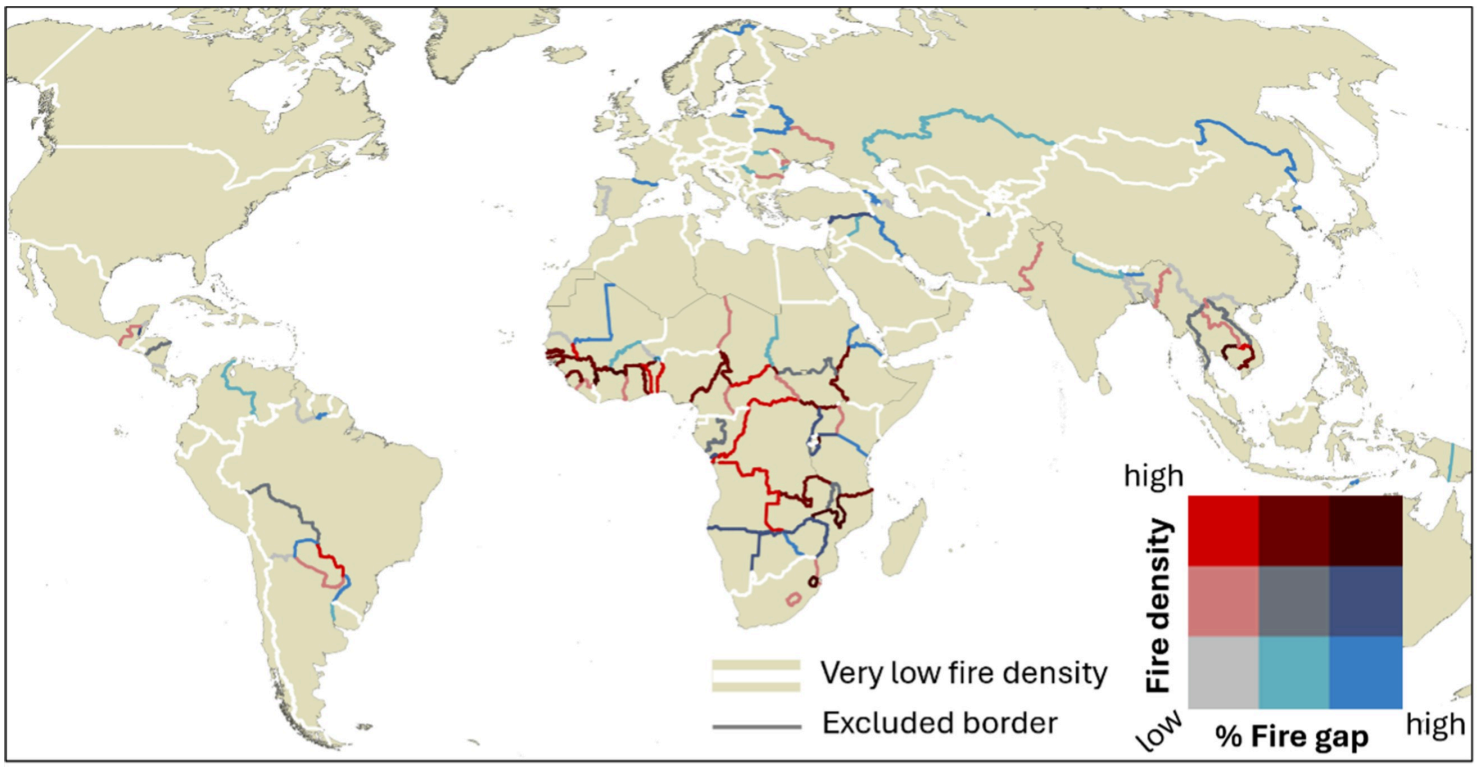


Figure 1

Fire burden versus relative fire gap in global borders

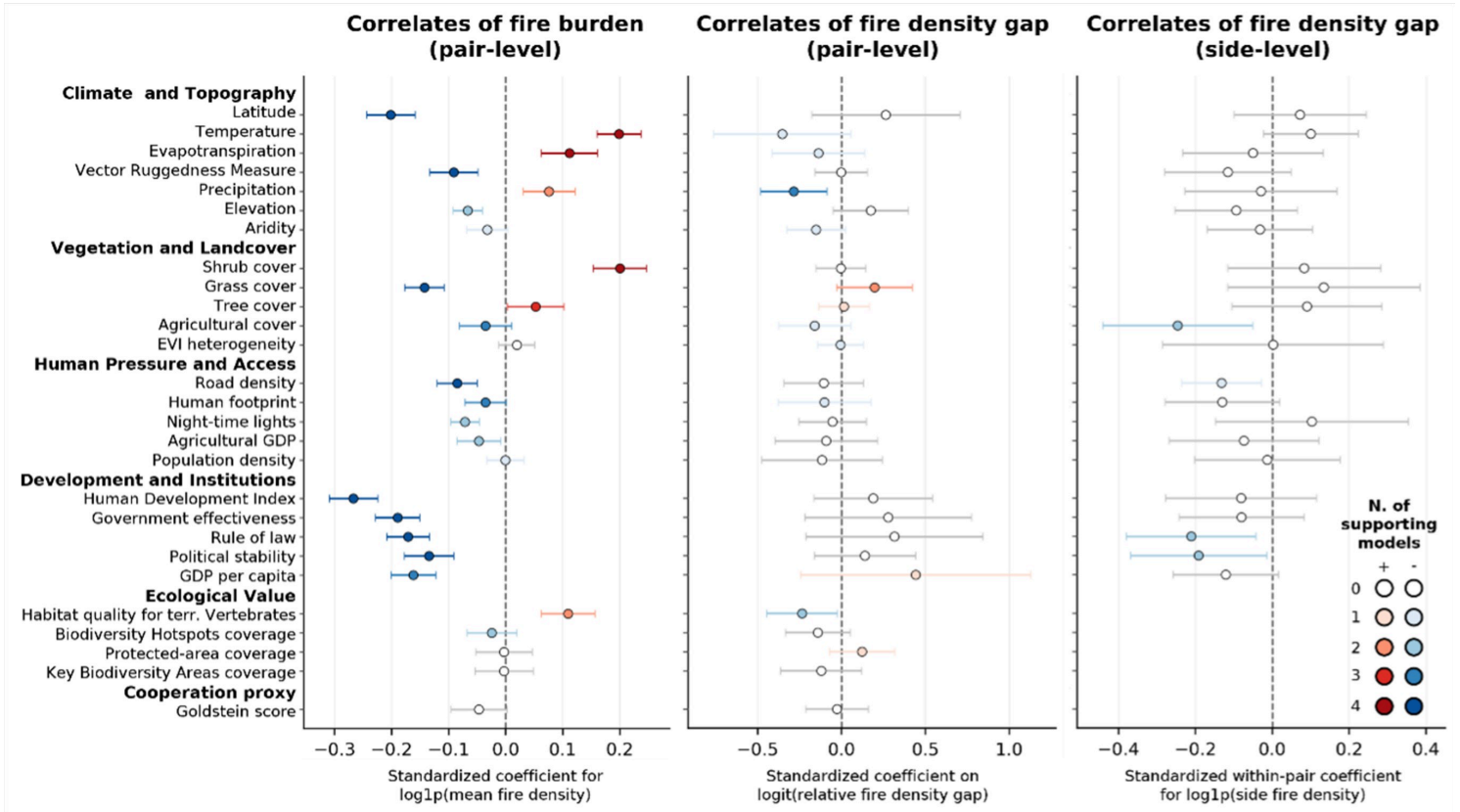


Figure 2

Predictors of border-pair fire burden and cross-border fire mismatch. Points show standardized coefficients from the main model in each panel, and horizontal bars show 95% confidence intervals. Color intensity indicates the number of model specifications in which the predictor was significant at unadjusted P ≤ 0.05, including the displayed main model. FDR-adjusted q values are reported in Supplementay Tables 3–5 Red indicates positive coefficients, blue indicates negative coefficients, and white indicates no significant support in any model specification. Left panel: fire burden models, including all-pair OLS-HC3 on log1p(mean fire density) as the main model, and three sensitivity models: active-fire OLS-HC3, positive fire Gamma log-link, and active-fire Gamma log-link. Center panel: relative fire gap models, including the active-fire OLS-HC3 model controlling for mean fire burden as the main model, and two sensitivity models: active-fire without mean-fire control and all-pair controlled model. Right panel: within-pair side-level fire density models, including the active-fire within-pair model as the main model and the all-pair within-pair model as sensitivity; both models used pair demeaning and standard errors clustered by border pair. Models were fitted separately for each predictor.

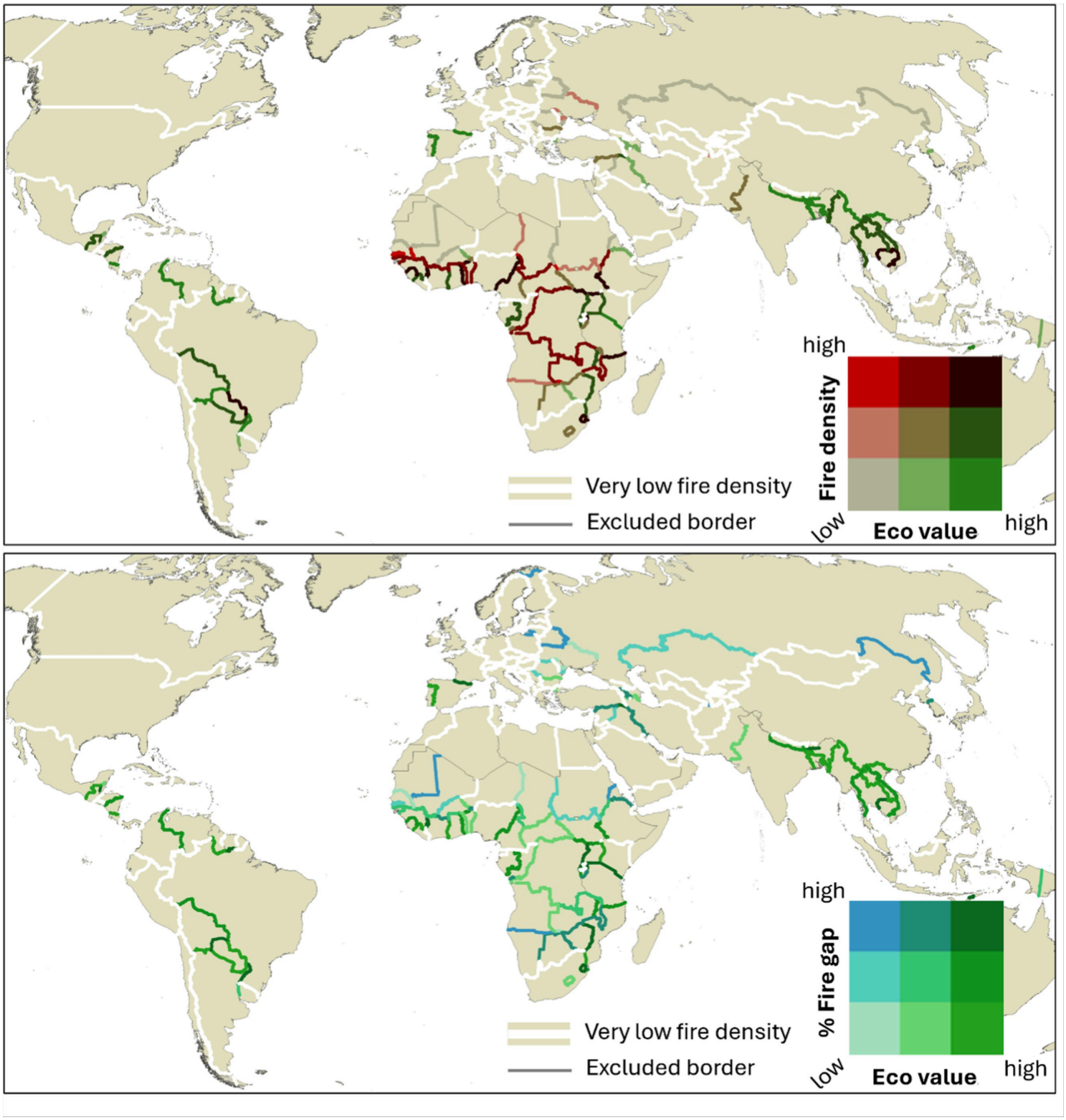


Figure 3

Top: Fire burden vs ecological value of global borders. Bottom: Relative fire gap vs ecological value of global borders.

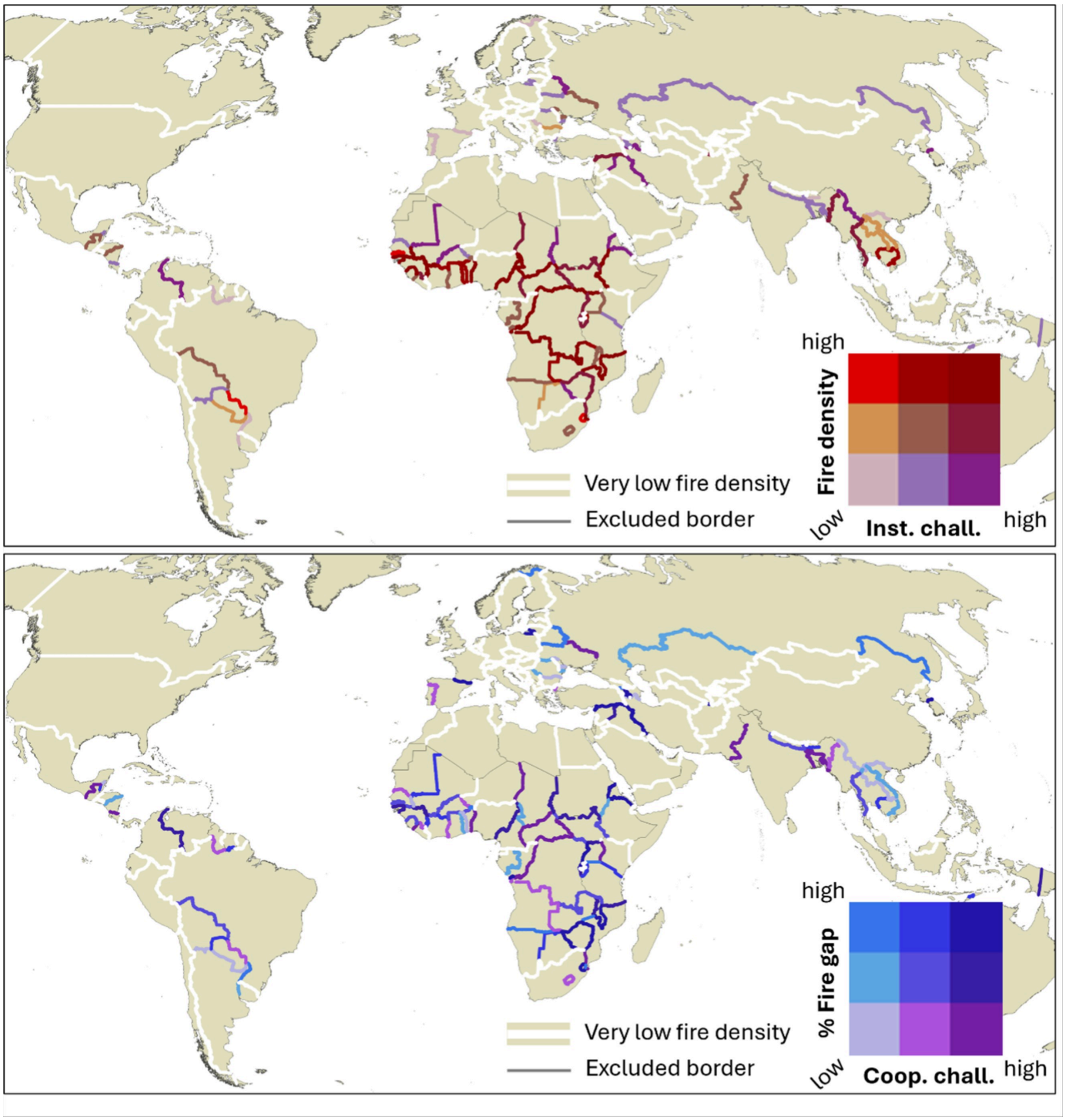


Figure 4

Top: Fire burden vs Institutional challenge of global borders. Bottom: Relative fire gap vs Cooperation challenge of global borders.

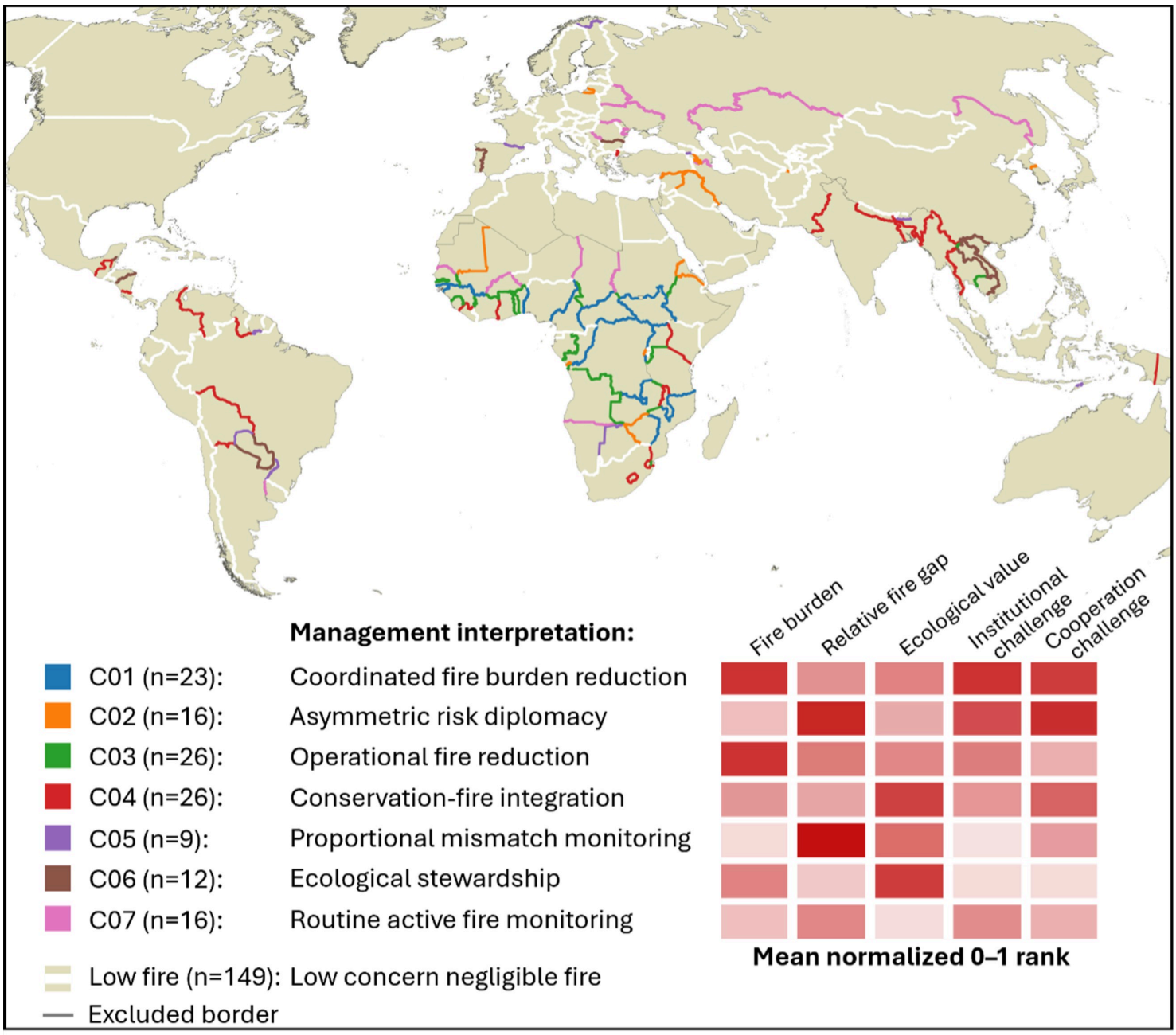


Figure 5

Data-driven fire management clusters for international border pairs. Active-fire border pairs were grouped using k-means clustering based on five standardized variables: mean fire burden, relative fire gap, ecological value, institutional challenge, and cooperation challenge. Negligible or very low fire pairs were not clustered and are shown as a separate low concern class. The map shows the spatial distribution of the seven active-fire clusters, and the legend summarizes each cluster's mean rank for the five clustering variables (heatmap values from 0 to 1) and the dominant management interpretation.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- LegendforSupplementaryData1.xlsx
- SupplementaryData1.xlsx
- SIanonymous.docx