From Maps to Mandates: Multitemporal Vegetation Cover Analysis as a Tool to Evaluate Environmental Judicial Decisions

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Abstract

This study examines the use of multitemporal vegetation cover analysis as a tool to assess the ecological effectiveness of judicial decisions that recognize the rights of nature, using Colombia's 2016 T-622 decision on the Atrato River as a case study. Using satellite data from MapBiomas and generalized additive models (GAMs), we evaluated changes in ten types of vegetation cover between 2006 and 2023 across collective territories governed by Afro-Colombian community councils and Indigenous reservations. Our results reveal a sustained loss of natural cover, particularly in community councils, driven by expanding mining and infrastructure activities, while Indigenous reservations experienced more limited transformations. We identified distinct patterns of change linked to historical, political, and social factors such as armed conflict, extractive concessions granted without prior communities consultation, and differing governance systems. Despite the legal recognition of the river as a rights-bearing entity, territorial impacts persist—highlighting the need to strengthen monitoring mechanisms, incorporate ecological indicators from the outset of legal rulings, and anchor implementation in environmental and ethno-territorial justice frameworks. Our findings demonstrate that, when properly contextualized, vegetation cover analysis can provide critical evidence to evaluate the material effectiveness of judicial decisions in biocultural territories.

Keywords: Bioculturality, environmental judicial assessment, ethno-territorial governance, ecosystem indicators, environmental justice, judicial compliance, ruling monitoring, territorial follow-up.

Resumen

Este estudio analiza el uso del análisis multitemporal de coberturas vegetales como herramienta para evaluar la efectividad ecológica de sentencias judiciales que reconocen derechos de la naturaleza, tomando como caso la Sentencia T-622 de 2016 sobre el río Atrato en Colombia. Mediante datos satelitales de MapBiomas y modelos aditivos generalizados (GAM), evaluamos los cambios en diez tipos de cobertura vegetal entre 2006 y 2023 en territorios colectivos de consejos comunitarios afrodescendientes y resguardos indígenas. Los resultados muestran una pérdida sostenida de coberturas naturales, especialmente en consejos comunitarios, asociada al avance de actividades mineras y de infraestructura, mientras que los resguardos presentaron transformaciones más limitadas. Identificamos patrones diferenciados de cambio vinculados a factores históricos, políticos y sociales, como el conflicto armado, las concesiones extractivas sin consulta previa y las formas de gobernanza propias. A pesar del reconocimiento jurídico del río como sujeto de derechos, los impactos territoriales persisten, lo que sugiere la necesidad de fortalecer los mecanismos de monitoreo, incorporar indicadores ecológicos desde la redacción de las sentencias, y anclar su implementación en procesos de justicia ambiental y étnico-territorial. Nuestros resultados muestran que el análisis de coberturas vegetales, cuando se contextualiza adecuadamente, puede aportar evidencia clave para evaluar la eficacia material de decisiones judiciales en territorios bioculturales. Una versión completa en español de este manuscrito se encuentra disponible como material suplementario.

Palabras clave: Bioculturalidad, cumplimiento judicial, evaluación judicial ambiental, gobernanza étnico-territorial, indicadores ecosistémicos, justicia ambiental, monitoreo de sentencias, seguimiento territorial.

Introduction

In the face of growing environmental challenges, the protection of critical ecosystems and the implementation of effective nature conservation policies have become global priorities (Freudenberger et al., 2013; Pyke, 2007). Among the most innovative approaches to emerge in legal and environmental spheres is the recognition of the rights of nature. Initially proposed by Christopher Stone in 1972, this paradigm suggests that natural entities can hold legal rights, integrating ecological principles into traditional legal frameworks (Stone, 1972). In Colombia, this concept materialized through the landmark 2016 T-622 decision, which recognized the Atrato River as a rights-bearing subject and established a legal mandate for its protection, conservation, and restoration by the Colombian State (Richardson & Bustos, 2022).

However, translating such legal decisions into tangible ecological outcomes remains a major challenge. As a formal mechanism for monitoring compliance, Colombia's Constitutional Court tasked the Office of the Inspector General with coordinating follow-up on the decision, in collaboration with the Comptroller General and the Ombudsman's Office. These institutions are responsible for requesting updates from the relevant agencies named after the Court's orders. Consequently, the Ministry of Environment and Sustainable Development, together with other government entities and in dialogue with the Collegiate Body of "Guardians of the Atrato", has produced a semiannual report submitted to the Oversight Committee. Yet, the indicators used to assess progress have been limited. It was not until the sixth report in 2020 that the analysis of natural and artificial cover changes in riparian zones was introduced as an environmental indicator, and even then, the results remain partial and inconsistent. Likewise, the observable outcomes in terms of ecological restoration and biodiversity conservation have been erratic.

Against this backdrop, a fundamental question arises for environmental law: can vegetation cover analysis be used as a tool to measure the effectiveness of decisions that recognize nature as a rights-bearing entity? This study is based on the premise that, while not a standalone or exhaustive indicator, multitemporal land cover analysis provides a useful, cost-effective, and replicable approach to monitor the ecological impacts of such legal decisions over the medium and long term.

The Atrato River case offers a critical setting for this assessment. Its watershed is vital for regulating the hydrological cycle, mitigating climate change, and sustaining biodiversity (Winemiller et al., 2016). Moreover, the basin is inhabited by Afro-Colombian communities organized into community councils and by Indigenous peoples who exercise territorial autonomy through legally recognized reservations. Both forms of collective governance are established in Colombian law (Law 70 of 1993; Law 160 of 1994; and Law 89 of 1890, respectively), and play a central role in territorial protection, resource management, and the defense of communal life (Rogelis Rincón et al., 2022). These communities have historically maintained a symbiotic relationship with the river, which serves as a source of livelihood, transportation, and cultural identity. Nevertheless, the basin continues to face significant pressures from deforestation, mining, and agricultural expansion (Richardson & Bustos, 2022), as well as the ongoing effects of armed conflict (Rogelis Rincón et al., 2022).

In addition to the T-622 decision, four other major political developments over the past two decades have shaped the territorial and environmental dynamics of the region: (1) the

National Mining Development Plan (2010–2019), which promoted the expansion of extractive industries; (2) the Victims and Land Restitution Law (Law 1448 of 2011) and its ethnic-focused decrees, which sought to repair territorial harm; (3) the Chocó civic strike, which brought national attention to the region's structural neglect by the state; and (4) the Peace Agreement with the FARC-EP (2016), which reconfigured territorial control and introduced the Development Programs with a Territorial Focus (PDET). Together, these events create a highly complex landscape for evaluating ecological impacts resulting from legal decisions.

In this study, we propose that multitemporal vegetation cover analysis can serve as a complementary, technically robust, and low-cost tool for assessing the ecological effectiveness of judicial decisions that recognize nature as a subject of rights. Vegetation cover is not only essential to ecosystem stability but also provides a quantifiable indicator of the impact of human interventions and conservation policies, as it is closely linked to resource use, mining, and other extractive activities involving local communities (Ang et al., 2021; Feng et al., 2020). Based on this premise, the goal of this study is to analyze changes in land cover in the Atrato River basin between 2006 and 2023, evaluating whether these transformations reflect differentiated impacts before and after the 2016 T-622 decision. We anticipate that if the decision has had a positive effect on ecosystem protection, we will observe a deceleration in the loss of natural cover or even signs of recovery in some areas. We also expect results to vary by governance type, with greater restoration progress predicted in areas managed by local communities compared to those under state control or intense extractive pressure.

This study addresses a critical knowledge gap: the lack of empirical research that quantifies the real-world ecological impacts of legal decisions. Understanding how these policies affect ecosystems will not only help improve the implementation of conservation measures in Colombia but also offer a replicable model for evaluating the effectiveness of nature rights in other contexts.

Methods

Study Area Delimitation

We delineated the study area by generating a 500-meter buffer around the main channel of the Atrato River using QGIS (v. 3.34.10-Prizren), to capture land use changes in riparian zones where most environmental transformations are concentrated. This buffer width was chosen because the river channel exceeds 300 meters in several sections, particularly in the middle reaches and near the river mouth. We then intersected the buffer with the boundaries of Afro-Colombian community councils and indigenous reservations, defining specific subareas that allowed us to analyze the role of each collective group in the ecological restoration of the river from both social and territorial perspectives.

Characterization of Land Cover and Land Use Changes

We analyzed land cover and land use changes using Landsat data from Google Earth Engine at 30 m resolution. We selected ten classes: four natural covers (Forest, Flooded Forest, Wetland, and Mangrove), one agricultural (Mosaic of Agriculture/Pasture), three associated with infrastructure and extractive activities (Urban Infrastructure, Mining, and

Other Non-Vegetated Areas), and two transversal categories (River and Beaches/Dunes/Sandbanks). These classes—hereafter referred to as "covers"—enabled us to assess ecosystem health, given the key role of forests in hydrological regulation, carbon sequestration, and biodiversity conservation.

After retrieving land cover data for the Atrato River basin, we conducted a zonal histogram analysis to quantify the area corresponding to each cover type over an 18-year period (2006–2023). The land cover and land use data used in this analysis were sourced from the MapBiomas database – Collection 2.0 of the Annual Series of Land Cover and Land Use Maps for Colombia, accessed on December 1, 2024, through the Google Earth Engine MapBiomas User Toolkit (version 1.33.0). Additionally, we used the WorldClim database (Fick & Hijmans, 2017) to obtain the maximum monthly precipitation per territory, ensuring spatial and temporal compatibility with the MapBiomas land cover data.

Data Analysis

To examine changes in vegetation cover across communities along the Atrato River between 2006 and 2023, we applied generalized additive models (GAMs), which are well-suited for modeling nonlinear relationships between cover and time (Wood, 2017). Prior to modeling, we conducted normality (Shapiro–Wilk) and homoscedasticity (Levene) tests, both of which revealed deviations ($p < 0.5$). However, because GAMs do not require strict assumptions of linearity or normality, these conditions did not compromise the validity of the models. We also assessed homoscedasticity in the residuals of the fitted models.

We organized the data by cover class, community, year, and area (hectares). Outliers were removed using the interquartile range (IQR) method (Tukey, 1977), retaining only values within Q1–1.5×IQR and Q3+1.5×IQR to reduce the influence of extreme values. Given the high variability among communities and cover types, we log-transformed the area variable (log(Area + 1)) to stabilize variance and improve distributional properties. Cover types with zero values across all years within a given community were excluded from the analysis.

To determine whether the area of each cover type changed significantly over time within each community, we fitted GAMs for each cover–community combination using the gam function from the *mgcv* package in R (Wood, 2011), with a smooth interaction term for year and cover (bs = c("cr", "re")) and a random effect for community (s(ID, bs = "re")). We tested the inclusion of precipitation as an explanatory variable, but an ANOVA ($Pr > Chi = 0.576$) indicated it did not contribute significant variance, so we opted for a more parsimonious model excluding it. Model fit was evaluated using the REML criterion and explained deviance. To interpret results, we applied F-tests, considering nonlinear relationships significant when $p < 0.05$ and effective degrees of freedom (EDF) were non-zero. We also generated GAM-based predictions and fitted linear regressions by cover and community to estimate temporal slopes, assessing their significance using t-tests. A change was considered significant if the 95% confidence interval of the slope did not include zero. Trends were visualized with smoothed lines and confidence bands, and the direction and magnitude of effects were plotted using error bars. All figures employed colorblind-safe palettes.

To assess whether the declaration of the T-622 judicial decision influenced trends in vegetation cover change over time, we applied the nonparametric Brunner–Munzel test

(Brunner & Munzel, 2000), grouping years into pre-decision (2006–2015) and post-decision (2016–2023) periods. This test, robust to non-normal distributions and outliers, is well-suited for ecological data with heterogeneity and data pairing. Only communities with complete data across both periods were included. Each record comprised Cover Type, Community ID, Year, and Area. We conducted the test for each combination of community and cover type using the brunner.munzel.test function from the *lawstat* package (Gastwirth et al., 2006) in R.

As a complementary analysis, we explored whether cover changes varied across five presidential terms (2006–2010, 2011–2014, 2015–2018, 2019–2022, and 2023) by introducing a categorical variable for period classification. No significant differences in cover were found across these periods (all $p > 0.05$), so we did not pursue this analysis further. All analyses were conducted in R version 4.4.2 (R Core Team, 2024). The data used in the analysis is provided as supplementary material.

Results

The analysis included 19 Afro-Colombian community councils, and 9 indigenous reservations located within the 500-meter buffer surrounding the Atrato River. Of these, 2 community councils are located in the department of Antioquia, while the remaining ones fall within the department of Chocó (Table 1, Figure 2).

Land Cover Trend Models

The GAMs fitted for community councils and indigenous reservations explained a substantial portion of the variance in the data, 63.7% and 68.5%, respectively (Table 2). In both cases, the smoothed interaction terms between Year and Cover Type were highly significant ($p < 2e-16$), indicating that cover area dynamics changed in distinct ways over time. Similarly, the random effects for community ID were also significant ($p < 2e-16$), suggesting notable spatial variability in land cover trajectories.

Trend analysis revealed marked differences among cover types. In community councils, we observed significant declines in forest, mangrove, wetland, other natural non-vegetated areas, and mosaic of agriculture and/or pasture cover (Table 2, Figure 3). In contrast, some cover types increased significantly in extent, including flooded forest, beaches and dunes, urban infrastructure, mining, and rivers. In indigenous reservations, similar trends were observed in some categories, with significant decreases in forest, wetlands, and mosaic of agriculture and/or pasture (Figure 4). In contrast, other natural non-vegetated areas and river cover increased significantly.

Comparison of Cover Types Before and After 2016

The Brunner–Munzel test did not detect significant differences in the overall distribution of land cover areas in community councils before and after 2016 ($p = 0.833$), suggesting that general cover changes during this period were not statistically pronounced (Table 2). However, when analyzing individual cover types, we observed significant changes in specific categories. Notably, mangroves ($p < 2e-16$) and mosaic of agriculture and/or pasture ($p = 0.016$) experienced significant reductions after 2016, while urban infrastructure showed a slight but significant increase ($p = 0.048$) (Figure 5).

In indigenous reservations, the Brunner–Munzel test also indicated no significant difference in total cover before and after 2016. However, at the level of individual cover types, other natural non-vegetated areas and river cover increased significantly ($p = 0.001$ and $p = 0.006$, respectively). Wetlands showed a declining trend that approached statistical significance ($p = 0.070$) (Table 2, Figure 6).

Discussion

Vegetation Cover Analysis as a Complementary Tool to Evaluate the Effectiveness of Environmental Judicial Decisions

Our findings show that multitemporal vegetation cover analysis can serve as a complementary technical tool for evaluating the ecological effectiveness of judicial decisions that recognize nature as a rights-bearing entity. This approach is cost-effective, replicable, and accessible to both institutions and communities, and it enables objective comparisons of ecosystem conditions before and after legal or policy interventions. Its comparative and temporal scope makes it particularly useful for monitoring environmental impacts over the medium and long term, especially in settings with weak or inconsistent institutional evaluation systems. Moreover, when data on land cover transitions are available, this analysis can help interpret ecological dynamics more precisely, revealing not only visible changes but also the forces driving them and the policies needed to address them.

For vegetation cover analysis to be useful in evaluating the effectiveness of environmental judicial decisions, it must be acknowledged that ecosystems respond over long time scales, and that processes of degradation or restoration do not occur immediately following legal interventions. This is particularly true in humid tropical ecosystems such as those of the Chocó region, where recovery depends on previous disturbance levels, floristic composition, and edaphic conditions (Isaacs Cubides & Ariza, 2015; Poorter et al., 2023). Additionally, the analysis must be contextualized within the social and political dynamics of the territory (Santos, 1990). In the case of the Atrato, the impacts of the judicial decision cannot be separated from armed conflict, extractivism, and the reconfiguration of territorial control following the Peace Agreement, factors that have shaped land use and environmental pressure (Rogelis Rincón et al., 2022).

Whereas classical conservation theories prioritized wilderness and intact habitats while excluding humans (Mace, 2014), more recent approaches emphasize the central role of communities in ecological restoration, equating ecosystem recovery with the well-being of those who inhabit the land (Ceccon, 2022, 2024; Nelson et al., 2024; Nepstad et al., 2006). In this framework, vegetation cover analysis should be understood as a baseline within comprehensive monitoring systems that integrate social, ecological, and cultural dimensions. This perspective is especially important in biocultural territories, where nature is woven into the spiritual, symbolic, and economic fabric of communities, as recognized by Law 70 of 1993 and constitutional jurisprudence concerning the collective rights and cosmovisions of Afro-descendant and Indigenous peoples.

Dynamics of Land Cover Change by Type of Collective Territory

The analysis revealed distinct patterns of land cover transformation between community councils and indigenous reservations, although both registered losses in natural cover. In community councils, this reduction was accompanied by increases in urban infrastructure and mining, indicating sustained human pressure. Mangrove loss was particularly notable in areas such as the Consejo Comunitario Mayor del Bajo Atrato, located in the Gulf of Urabá, likely associated with both legal port development projects (e.g., Puerto Antioquia) and illegal activities, as well as armed conflict and territorial appropriation (Comisión de la verdad, 2021).

The increase in urban infrastructure within community councils is significant, as it may reflect the imposition of illegal activities such as the installation of coca processing laboratories without community consent, as reportedly occurred in the Consejo Comunitario de Vigía de Curvaradó and Santa Rosa de Limón (Comisión Intereclesial de Justicia y Paz, 2013). In some cases, this expansion may also be linked to mobility restrictions imposed by armed actors, leading to conditions of confinement in which communities are forcibly restricted to their territories. Mining cover, which was already significant before the T-622 judicial decision, showed a slight deceleration after 2016. This may suggest partial containment linked to increased institutional and community oversight following the river's designation as a rights-bearing entity, though insufficient to reverse the overall trend.

In indigenous reservations, although changes were more limited, they are nonetheless concerning. Declines were observed in forest, wetlands, and mosaic of agriculture/pasture cover, alongside increases in river area and other natural non-vegetated areas. Unlike community councils, we found no evidence of mining activities within these reservations in our analysis, possibly due to lower geographic exposure, more restrictive territorial management models, or stronger organizational structures that limit the entry of external actors (Restrepo, 2011). However, the increase in non-vegetated areas may reflect indirect degradation processes, such as deforestation in adjacent zones, hydrological alterations, or agricultural expansion.

The increase in river cover observed in both groups may reflect sedimentation processes, changes in water flow, or lateral expansion of the river channel—likely driven by forest cover loss and intensive use of riparian zones (Winemiller et al., 2016). In indigenous reservations, this trend also suggests cumulative impacts originating from external areas, given the hydrological connectivity of the basin. An increase was also observed in the cover of beaches, dunes, and sandbanks, which may be linked to mangrove degradation and changes in sediment dynamics. These transformations affect not only the ecological functioning of the river but also its navigability, particularly for Afro-descendant communities who depend on the Atrato for transportation and subsistence. In this regard, restoration strategies must go beyond traditional land-based approaches and focus on reestablishing the ecological complexity of the fluvial system, including wetlands, mangroves, and hydro-sedimentary dynamics that sustain the biocultural integrity of the territory.

The differences observed reflect how ecological trajectories are shaped by institutional, ethnic, and political factors. While both groups face common threats such as extractivism and weak state presence, their responses and levels of vulnerability differ, requiring tailored evaluations that account for the specific characteristics of each governance model. Despite the analytical separation between indigenous reservations and community councils, in practice they share an interdependent biocultural territory within the Atrato basin. Their boundaries touch, they share watersheds, ecological corridors, and common threats, generating constant dynamics of cooperation or conflict that are essential for interpreting the ecological transformations observed.

Although they are governed by different logics, land-use practices in the Atrato's collective territories have evolved in constant interaction. Indigenous peoples follow customary rules oriented toward conservation, while community councils combine production, subsistence, and territorial defense (Restrepo, 2011; Rogelis Rincón et al., 2022). This difference is reflected in the multitemporal analyses: indigenous reservations show greater ecological stability, in contrast to community councils, where transformations associated with mining and urban infrastructure are more pronounced. Part of this pressure stems from historic exposure to extractive activities, such as in COCOMOPOCA, where over 21 mining titles were granted without consultation between 2003 and 2008, covering 23% of the territory (González & Castro, 2023). Policies such as the "mining locomotive" initiative launched in 2010 further exacerbated these dynamics, often linked to illegal armed groups, consolidating extractive enclaves that displaced communities and fragmented both ecological and social fabrics (Rogelis Rincón et al., 2022). Thus, these changes largely reflect external impositions rather than community-driven decisions. Nonetheless, reducing this distinction to a binary of stability versus instability would be simplistic. Territorial trajectories are shaped by local governance conditions, access to resources, and adaptive capacity. In this context, the Collegiate Body of Guardians of the Atrato, bringing together representatives from both collectives, has emerged as an innovative experiment in intercultural governance.

Ecological changes cannot be understood in isolation across territories: processes such as deforestation and hydrological alteration transcend administrative boundaries. What happens upstream in Afro-descendant territories can directly affect indigenous reservations downstream. Therefore, the findings must be interpreted as part of an interdependent dynamic, shaped by community relations and the type of external intervention, whether state-led or extractive. Recognizing these interactions is key to understanding the true impact of the T-622 judicial decision and to promoting joint restoration strategies that integrate cultural diversity with ecological continuity throughout the Atrato basin (Ceccon, 2022; Nelson et al., 2024; Restrepo, 2011).

The Role of Indicators and the Drafting of Judicial Decisions

A central lesson from this analysis is the urgent need to include clear, measurable, and useful indicators in environmental judicial decisions. Although the 2016 T-622 decision was groundbreaking in recognizing the Atrato River as a rights-bearing entity, it lacks a monitoring framework with verifiable metrics to evaluate its implementation over time. This omission has hindered effective follow-up and led to divergent interpretations of what constitutes progress or regression.

In the early follow-up reports by the Ministry of Environment and the Collegiate Body of Guardians, most indicators were narrative or legal in nature—such as the number of meetings held or institutional frameworks established—and did not reflect tangible ecological changes. Only in the sixth report (2020) was vegetation cover analysis introduced, and in 2022, data on ecosystem loss were reported for the first time, including

3,450 hectares of forest lost between 2019 and 2021. However, this information was neither updated nor consolidated into a systematic evaluation tool. The lack of continuity underscores that monitoring mechanisms must be defined at the drafting stage of the decision, not left as generic tasks. To be effective, such rulings must include robust monitoring instruments developed through both technical and community participation. When properly contextualized, indicators such as vegetation cover can serve as a quantitative baseline to detect trends and risks of non-compliance.

This study shows that indicators should not be limited to technical functions, they must also fulfill political and pedagogical roles: enabling communities to understand, monitor, and demand enforcement of their territorial and environmental rights. In contexts such as the Atrato, where state presence has historically been weak, simple tools like land cover maps can strengthen local capacities to engage in restoration, planning, and environmental justice processes. We argue that the inclusion of indicators such as multitemporal vegetation cover analysis should be a structural requirement in future judicial decisions with ecological and territorial focus. However, these tools must be grounded in processes of consultation, intercultural dialogue, and respect for local epistemologies. As demonstrated by other experiences across Latin America, bioculturality is not merely a conceptual framework, but an ethical and practical condition for sustainability in territories with high ecological and cultural diversity (Díaz et al., 2018; Nepstad et al., 2006).

Legal and Juridical Implications

The 2016 T-622 judicial decision, which recognized the Atrato River as a rights-bearing subject, marked a milestone in Colombian environmental law and has become an international benchmark for ecological jurisprudence. However, this study reveals that such recognition has not been sufficient to halt landscape transformation in the basin. The persistence of ecological degradation, despite normative progress, raises serious questions about the practical effectiveness of nature's rights (Foster & Bell-James, 2024; Richardson & Bustos, 2022).

Our findings suggest that incorporating ecological indicators, such as multitemporal vegetation cover analysis, can help address the operational gap in rulings like T-622. These indicators allow for the evaluation of ecosystem integrity and health—central principles of the rights of nature—and facilitate technical monitoring of territorial impacts. Nonetheless, their effectiveness depends on several enabling conditions: (1) coordinated institutional governance, (2) democratic access to information guided by a human rights framework and tools like the Escazú Agreement, (3) integration of diverse knowledge systems, (4) minimum security conditions in conflict-affected areas, and (5) availability and efficient use of financial resources (González & Castro, 2023; Ministerio de Ambiente y Desarrollo Sostenible, 2019).

In territories such as the Atrato, marked by multiple forms of violence, vegetation cover analysis must be contextualized in relation to armed conflict, mining expansion, and institutional weakness. Afro-descendant community councils have been particularly affected by the granting of mining concessions without prior consultation and by illegal extractive economies supported by armed actors (González & Castro, 2023; Rogelis Rincón et al., 2022). These conditions hinder the effective implementation of decisions like T-622 and highlight the need to accompany them with comprehensive territorial reparation strategies that acknowledge the historical legacy of exclusion and violence.

From a broader legal perspective, our findings indicate that judicial decisions on the rights of nature still do not fully diverge from conventional environmental law rulings. Although they aim to recognize the intrinsic value of ecosystems, they continue to face the same structural limitations as other state-led restoration efforts. We argue that such rulings should include specific implementation parameters, with indicators focused on biocultural restoration and the protection of lifeways linked to territory (Díaz et al., 2018). This requires a shift toward legal interculturality, in which state law engages in dialogue with the normative systems of Indigenous and Afro-Colombian peoples, acknowledging their forms of governance and territorial stewardship. The Atrato case demonstrates that legal effectiveness depends less on the normative text and more on the capacity to build alliances with the communities that have historically cared for these ecosystems. As legal pluralism suggests, only a legal architecture that incorporates such diversity can produce real transformations (Díaz Ocampo, 2018; Laguna Delgado et al., 2020).

Judicial decisions should be understood as opportunities to activate a more coherent, progressive, and participatory state response. Their implementation cannot rely solely on corrective actions, but must be embedded in coordinated public policy, with verifiable goals and funding consistent with the principle of progressive realization of human rights. Effective enforcement requires interinstitutional coordination, monitoring platforms, and community participation. Within this framework, vegetation cover analysis can serve as a powerful tool to track the effectiveness of ecological judicial decisions, provided it is embedded in a legal architecture that acknowledges territorial complexity, respects normative systems of local communities, and addresses the historical challenges of conflict, extractivism, and inequality. In this sense, environmental justice must go hand in hand with ethnic and territorial justice.

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Tables

Table 1. Territorial distribution of community councils and indigenous reservations intersecting the defined buffer within the Atrato River basin. The table presents a classification of the community councils and indigenous reservations located in the departments of Antioquia and Chocó analyzed in this study, indicating their municipality, official name, community identification code, corresponding DANE code, and the territorial area managed (in hectares). These community councils and indigenous reservations play a key role in the environmental and social governance of the territory, including the implementation of conservation and ecological restoration policies in the context of the recognition of the rights of nature.

Department	Municipality	Name	Community / Reservation ID	DANE code	Area (Ha)
Community councils					
Antioquia	Murindó	Consejo Comunitario Por El Desarrollo Integral	20125	2124	11328
Antioquia	Turbo	Consejo Comunitario de Bocas De Atrato y Leoncito	20030	2031	34367
Chocó	Quibdó	Consejo Comunitario Mayor Del Medio Atrato - Acia	20007	2007	695245
Chocó	Atrato	Consejo Comunitario de la Comunidad Negra de La Molana	20188	2190	1807
Chocó	Atrato	Consejo Comunitario Santo Domingo	20346	2236	1726
Chocó	Carmen del Darién	Consejo Comunitario del Río Curvaradó	20043	2051	46084
Chocó	Carmen del Darién	Consejo Comunitario de La Grande	20035	2048	13456
Chocó	Carmen del Darién	Consejo Comunitario de Vígia De Curvaradó y Santa Rosa De Limón	20055	2050	33909
Chocó	Carmen del Darién	Consejo Comunitario de Turriquitadó	20054	2041	9407
Chocó	Carmen del Darién	Consejo Comunitario del Río Montaño	20046	2049	25006
Chocó	Carmen del Darién	Consejo Comunitario del Río Domingodó	20044	2045	38988
Chocó	Lloró	Consejo Comunitario Integral De Lloro_Cocoillo	20169	2147	19426
Chocó	Lloró	Consejo Comunitario Mayor De La Organización Campesina Popular Del Alto Atrato - Cocomopoca	20165	2180	73317

Chocó	Río Quito	Consejo Comunitario de la Comunidad Negra del Corregimiento de la Soledad	20347	2237	188
Chocó	Riosucio	Consejo Comunitario de Los Ríos La Larga Y Tumaradó	20037	2047	107064
Chocó	Riosucio	Consejo Comunitario de la Cuenta del Río Cacarica	20024	2022	103024
Chocó	Riosucio	Consejo Comunitario Pedeguita Y Mancilla	20040	2046	48972
Chocó	Riosucio	Consejo Comunitario de La Cuenca Del Río Salaquí	20034	2044	57914
Chocó	Unguía	Consejo Comunitario Mayor Del Bajo Atrato	20124	2123	34736
Indigenous reservations					
Chocó	El Carmen de Atrato	El Doce Quebrada Borbollon (Embera Katio)	10269	1217	1185
Chocó	El Carmen de Atrato	Resguardo Indígena Sabaleta (Embera Katio)	10338	1219	610
Chocó	El Carmen de Atrato	El Dieciocho (Embera Katio)	10268	1797	1563
Chocó	El Carmen de Atrato	Abejero (Embera Katio)	10241	1575	230
Chocó	Atrato	El Fiera (Embera Katio)	10270	1763	4439
Chocó	Quibdó	Playalta, El Veinte Y El Noventa (Embera Katio)	10273	1246	3334
Chocó	Lloró	Embera De Lanas (Embera)	10351	1235	6400
Chocó	Lloró	Guadualito (Chocó) (Embera)	10277	1649	428
Chocó	Lloró	Hurtado Y Tegavera (Embera)	10280	1234	3225

Table 2. GAM results for community councils and indigenous reservations.

The table presents the results of the generalized additive models (GAM) for (A) community councils and (B) indigenous reservations. The first section of each model reports the parametric coefficients and the approximate significance of the smooth terms. The second section shows the predicted effects for each land cover type. The *slope* column indicates the estimated rate of change over time, with corresponding 95% confidence intervals. The *Trend* column indicates whether the change is positive (+) or negative (–), and asterisks (*) denote statistical significance ($p < 0.05$).

A. Community council

Parametric coefficients					
	Estimate	Std. Error	t value	Pr(>|t|)	
Intercept	1.591	0.092	17.220	<2e-16	***

Approximate significance of smooth terms					
	edf	Ref.df	F	p-value	
te(year, cover type)	18.71	178	172.7	<2e-16	***
s(ID)	16.79	17	71.7	<2e-16	***
R-sq.(adj)	0.672		Dev explained	63.70%	
-REML	3441		Scale est.	0.06404	
N	1848				

Predicted efects					
Cover type	Slope	CI Lower	CI Upper	Tendencia	
Forest	-0.0079	-0.0073	-0.0085	-	*
Mangrove	-0.0124	-0.0101	-0.0148	-	*
Flooded forest	0.0053	0.0049	0.0056	+	*
Wetland	-0.0123	-0.0113	-0.0132	-	*
Mosaic of agriculture and pasture	-0.0444	-0.0418	-0.0470	-	*
Beach, dune and sand spot	0.0599	0.0493	0.0706	+	*
Infrastructure	0.0307	0.0284	0.0330	+	*
Other natural non-vegetated area	-0.0198	-0.0178	-0.0217	-	*
Mining	0.0600	0.0548	0.0653	+	*
River	0.0174	0.0162	0.0185	+	*

B. Indigenous reservation

Parametric coefficients					
	Estimate	Std. Error	t value	Pr(>|t|)	
Intercept	1.3431	0.1655	8.115	<2e-16	***

Approximate significance of smooth terms

	edf	Ref.df	F	p-value	
te(year, cover type)	8.732	80	210.1	<2e-16	***
s(ID)	7.938	8	108.8	<2e-16	***
R-sq.(adj)	0.673		Dev explained	68.5%	
-REML	756.49		Scale est.	0.05333	
N	438				

Predicted efects

Cover type	Slope	CI Lower	CI Upper	Tendencia	
Forest	-0.0113	-0.0107	-0.0119	-	*
Wetland	-0.1149	-0.1068	-0.1230	-	*
Mosaic of agriculture and pasture	-0.0338	-0.0304	-0.0373	-	*
Other natural non-vegetated area	0.0973	0.0846	0.1100	+	*
River	-0.1085	-0.0957	-0.1214	-	*

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Table 3. Brunner-Munzel test results for land cover change before and after 2016. This table shows the results of the Brunner-Munzel rank-sum test for (A) community councils and (B) indigenous reservations. The first row of each section presents the global test statistic and corresponding p-value, along with the median of Log(Area) before and after 2016. A p-value less than 0.05 indicates a significant change in land cover following 2016. The second part of each section details the predicted effects by land cover type. The *p_value* column indicates whether the change is statistically significant ($p < 0.05$), highlighted with an asterisk (*) according to its order of magnitude.

A. Community council

Test Statistic	0.2099	p-value	0.8337	Me before 2016	5.92	Me after 2016	6.16
Predicted efects							
Cover type	Me before	Me after	W	CI Lower	CI Upper	p_value	
Forest	7.5888	7.4573	-1.1619	-0.3907	0.5964	0.2462	
Mangrove	8.0340	7.9322	-27.577	0.0709	0.1801	<2e-16	***
Flooded forest	8.8993	8.9202	0.6320	-0.4936	0.4167	0.5279	
Wetland	4.7493	4.7446	0.1689	-1.0405	0.8654	0.8661	
Mosaic of agriculture and pasture	4.6634	4.1190	-2.4355	0.0886	0.9128	0.0160	*
Beach, dune and sand spot	3.7136	4.6869	0.3215	-3.1155	2.9857	0.7495	
Infrastructure	3.2581	3.2958	1.9858	-0.5781	0.0800	0.0488	*
Other natural non-vegetated area	3.0445	2.8618	-0.3743	-0.2578	0.5196	0.7088	
Mining	5.9251	6.4846	0.8762	-2.5186	2.2927	0.3854	
River	7.8236	7.5101	0.5235	-0.9657	0.8981	0.6010	

B. Indigenous reservation

Test Statistic	-1.4999	p-value	0.1344	Me before 2016	5.64	Me after 2016	5.62
Predicted efects							
Cover type	Me before	Me after	W	CI Lower	CI Upper	p_value	
Forest	6.8763	6.8533	-0.6890	-0.1463	0.2717	0.4919	
Wetland	4.2228	3.0445	-2.0059	-0.4055	2.7621	0.0708	.
Mosaic of agriculture and pasture	5.5215	5.5255	-0.9565	-0.1363	0.4826	0.3406	
Other natural non-vegetated area	3.2581	4.3817	3.7470	-2.4044	-0.6169	0.0010	***
River	5.2729	2.8029	-2.7962	0.1464	3.0007	0.0065	**

Figures

Figure 1. Location map of the communities analyzed in the Atrato River basin.

Community councils (orange) and indigenous reservations (fuchsia) intersecting the 500-meter buffer around the Atrato River are shown.

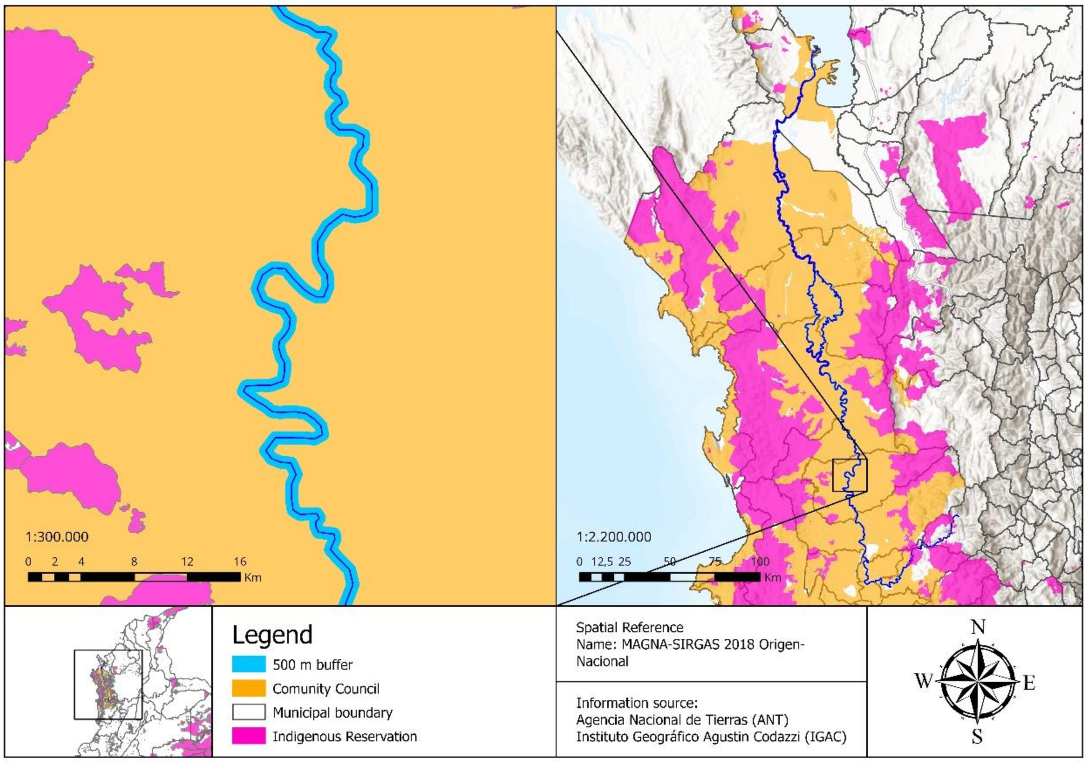

Figure 2. Trends in land cover change in community councils and indigenous reservations from 2006 to 2023. Estimated trends from generalized additive models (GAMs) are shown for different land cover types in community councils (A) and indigenous reservations (B) between 2006 and 2023. Colored lines represent adjusted trends for each community or reservation, identified by a unique code (colors in the legend). Dashed lines indicate the entry into force of Judicial Decision T-622 in 2016. Shaded areas around each line represent the 95% confidence interval of the GAM predictions, indicating model uncertainty in trend estimation.

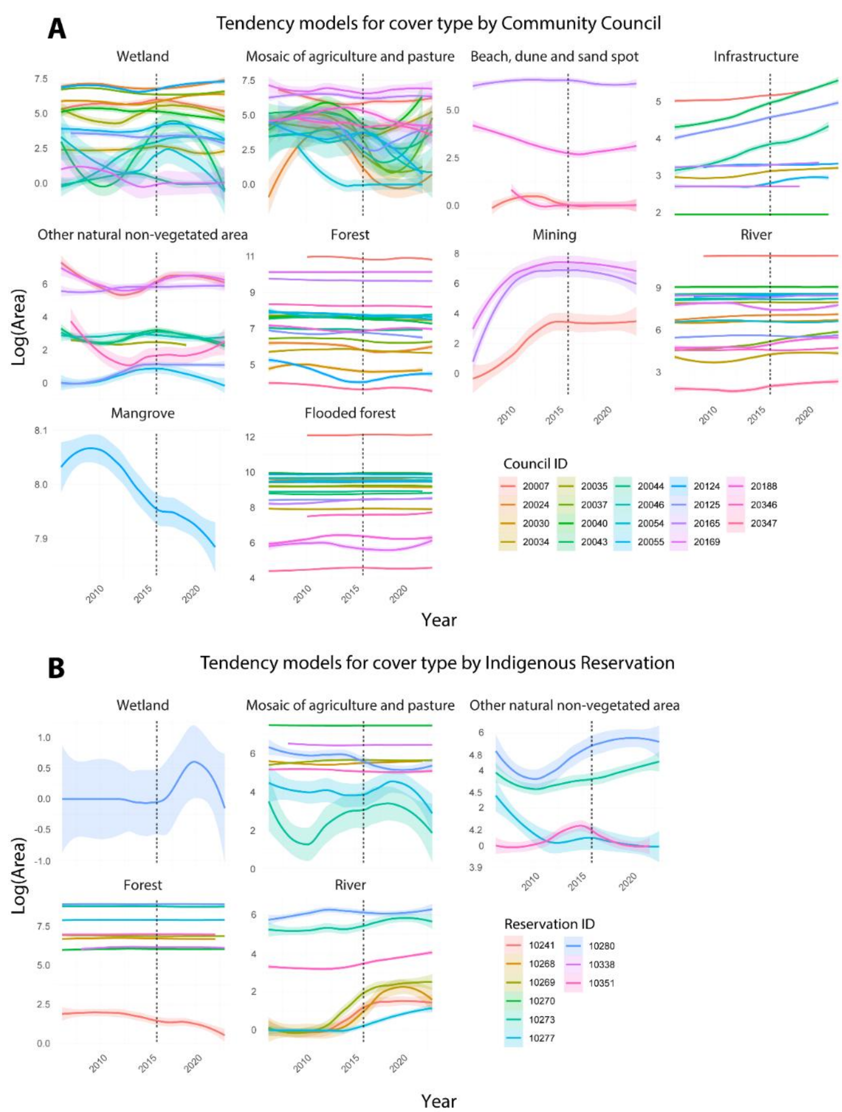

Figure 3. General GAM-adjusted trends for each land cover type in community councils between 2006 and 2023. (A) Estimated trends in area (in hectares) for different land cover types over time. Solid lines represent the estimated mean trend, and shaded bands indicate the 95% confidence intervals. (B) Estimated slope of change for each land cover type, with 95% confidence intervals. Positive values indicate an increase in cover, while negative values indicate a decrease. Dashed lines mark the year 2016, when Judicial Decision T-622 came into effect.

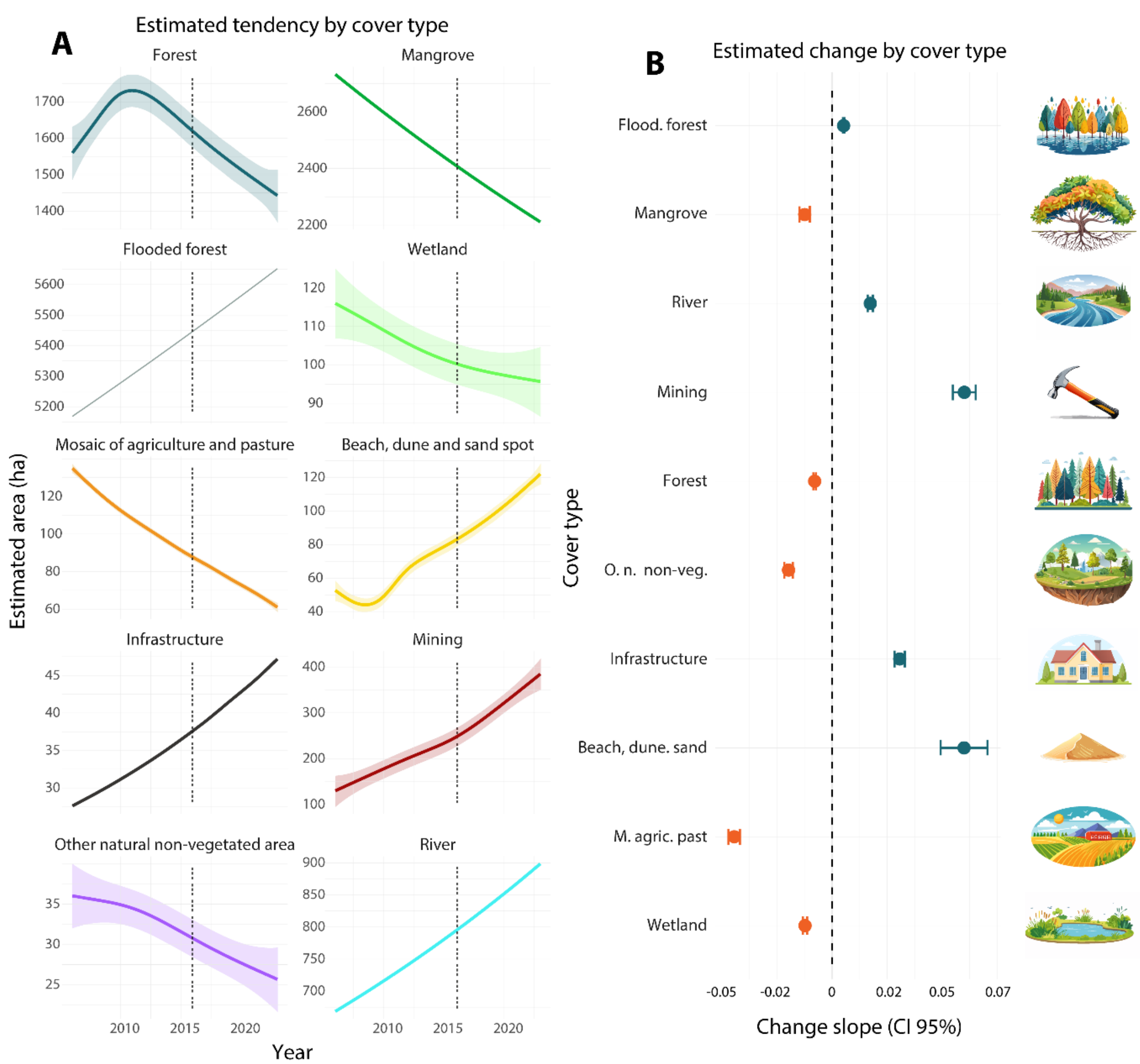

Figure 4. General GAM-adjusted trends for each land cover type in indigenous reservations between 2006 and 2023. (A) Estimated trends in area (in hectares) for different land cover types over time. Solid lines represent the estimated mean trend, and shaded bands indicate the 95% confidence intervals. (B) Estimated slope of change for each land cover type, with 95% confidence intervals. Positive values indicate an increase in cover, while negative values indicate a decrease. Dashed lines mark the year 2016, when Judicial Decision T-622 came into effect.

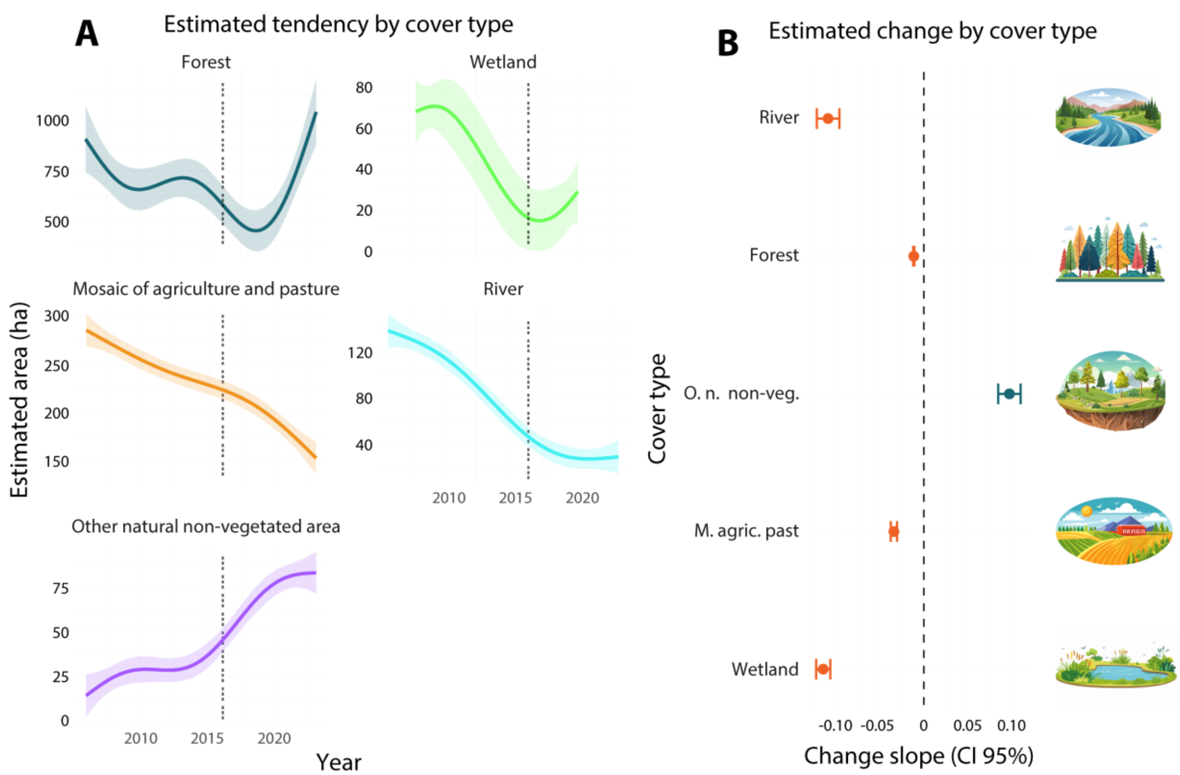

Figure 5. Density distribution and comparison of land cover area before and after Judicial Decision T-622 for community councils. (A) Density distribution of the area covered by different land cover types, comparing two time periods: before Judicial Decision T-622 (orange) and after the decision (blue). (B) Boxplot comparison of land cover area by type across both periods. p-values are indicated for cover types with statistically significant differences. In both panels, area values are presented as the logarithm of area: Log(Area).

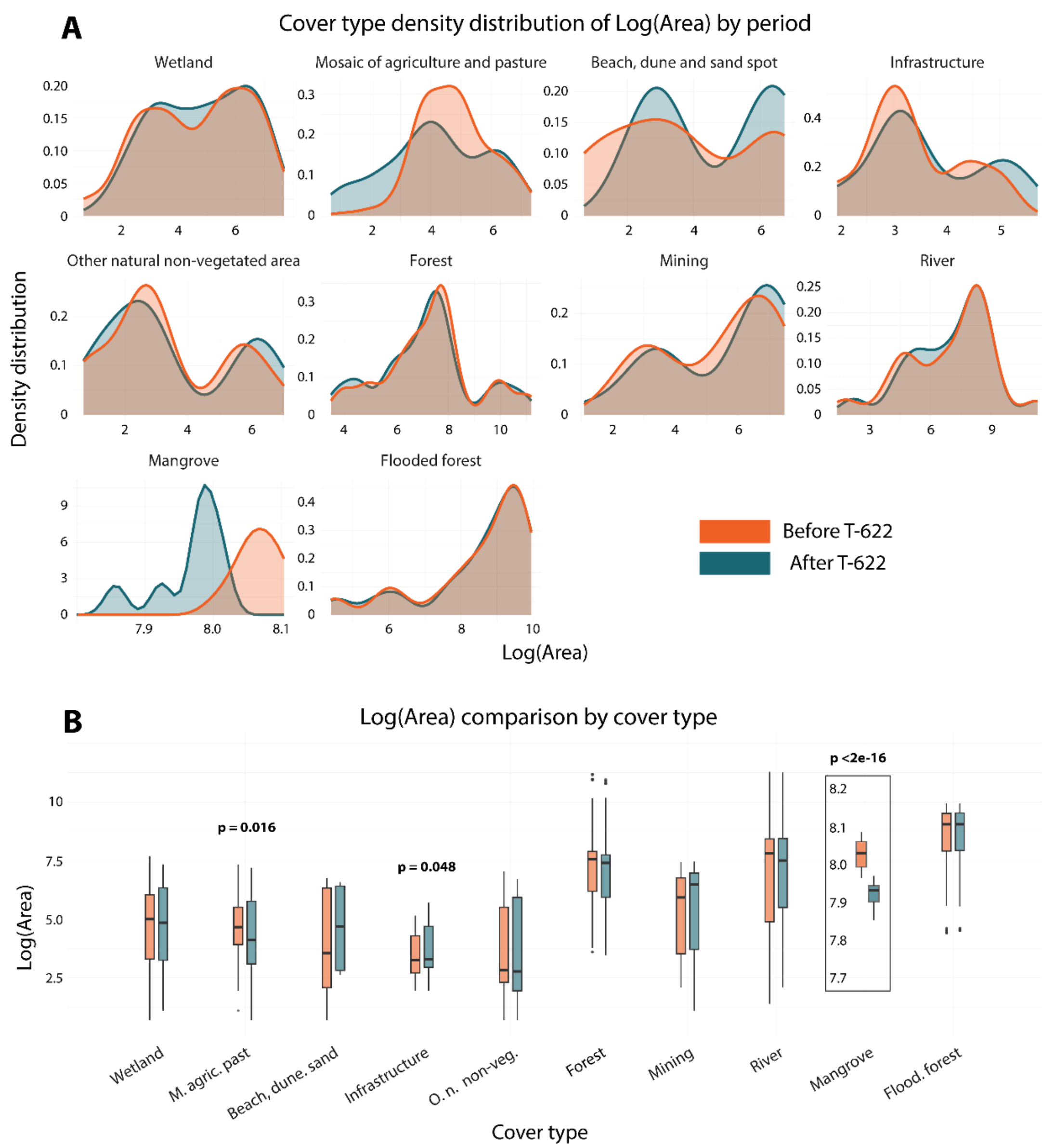

Figure 6. Density distribution and comparison of land cover area before and after Judicial Decision T-622 for indigenous reservations. (A) Density distribution of the area covered by different land cover types, comparing two time periods: before Judicial Decision T-622 (orange) and after the decision (blue). (B) Boxplot comparison of land cover area by type across both periods. p-values are indicated for cover types with statistically significant differences. In both panels, area values are presented as the logarithm of area: Log(Area).