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Armed conflict as a socio-ecological disturbance: identifying priority ecological restoration scenarios using fuzzy logic in Colombia

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Abstract

The armed conflict in Colombia has historically functioned as a socio-ecological disturbance transforming land cover and degrading ecosystems. The ecological restoration (ER) of these territories represents an opportunity within the framework of the Peace Agreement but requires prioritization tools that incorporate the uncertainty inherent in the conflict dynamics. This study develops a prioritization model for ER in Colombia using fuzzy logic, integrating conflict-related variables, biophysical factors, and socioeconomic factors into a hierarchical fuzzy inference system (HFIS) integrated into a Geographic Information System. The model generated five prioritization scenarios differentiated by conflict dynamics: Caribbean, Chocó-Magdalena Medio, Catatumbo-Arauca, Amazonia-Meta, and Nariño-Cauca. Results revealed that protected areas and collective territory have functioned as ecological refugees in high conflict intensity zones, playing a key role in implementing ER processes. The spatial overlap between the prioritized scenarios and municipalities included in the Territorially Focused Development Programs (Programas de Desarrollo con Enfoque Territorial, PDET) supports the model's consistency with post-conflict public policy instruments. For each scenario, differentiated ER strategies were identified, linked to existing policy instruments, recognizing demining as a cross-cutting process that must advance in coordination with ER. These findings show that ER in conflict-affected territories requires a differentiated territorial approach that acknowledges the heterogeneity of socio-ecological disturbances and integrates with the processes of territorial reparation and reconstruction of the Colombian post-conflict.

Introduction

Armed conflicts worldwide have led to significant deforestation and land-use change (Lavaux 2004; Dorondel et al. 2021; Pérez-Rincón et al. 2022), particularly in tropical biomes (Méndez-Garzón and Valánszki 2020) in Africa, Latin America and Asia (Ghosh and Ramesh 2023). In these contexts, environmental degradation is linked to the historical exploitation of resources, social exclusion and the use of natural resources to finance armed groups activities (Le Billon 2001). In Colombia, the internal armed conflict (IAC) began in the 1960s and lasted until 2016, when the peace agreement was signed with the guerrilla FARC-EP (Fuerzas Armadas Revolucionarias de Colombia-Ejército del Pueblo) (Centro Nacional de Memoria Histórica [CNMH] 2014). The period following this has therefore been referred to as the post-conflict.

The IAC has operated as a socio-ecological disturbance, producing various changes in land cover (Armenteras et al. 2019; 2013; Negret 2020). These effects have been exacerbated by its prolonged duration, link to unequal land access, and policies that favour an economic model based on the exploitation of natural capital (Castro-Núñez et al. 2017; Ruiz-Serna & Ojeda 2023). Furthermore, the resulting loss of biodiversity compromises the ecological foundations that have sustained ways of life, cultural practices and local community economies (Grima and Singh 2019). Dispossession has led to deteriorated socio-ecological conditions, primarily due to the loss or damage of ecosystem services and the constraints faced by communities in exercising governance over their territories (Almassi 2017; Pérez-Rincón et al. 2022).

This is significant because the post-conflict period opened a window of opportunity for investors and other armed groups to take territorial control and carry out extractive activities in areas previously dominated by FARC-EP, increasing deforestation in the country (Rodríguez et al. 2017; Prem et al. 2020). Murillo-Sandoval et al. (2021) found that during this period there was a vast wave of agricultural expansion, which increased this phenomenon by 40%. Similarly, Clerici et al. (2020) describe a dramatic and significant increase in the country's protected areas. However, certain dynamics of the conflict have had an impact on the conservation of specific areas, driven

by the need to maintain extensive forest cover to conceal trafficking routes or hideouts (Rodríguez et al. 2017; Benavides-Ossa et al. 2022). In this sense, although the post-conflict period began with the peace agreement, the war has not ended, it has been transformed through the emergence of new armed actors, who are driving territorial reconfigurations characterized by violence markets, disputes over illicit economies and new armed coalitions (Badrán 2023).

In this context, ER has already been used worldwide in post-conflict settings, including initiatives involving military forces in the safeguarding of protected areas (Machlis and Hanson 2008; Ghosh and Ramesh 2023) and restoration actions implemented in former military (Machlis and Hanson 2008, Nail 2018). However, some of these processes have been shown to fail due to a lack of community involvement, a lack of strategic planning and insufficient state participation (Ghosh and Ramesh 2023; Dorondel et al. 2021).

In Colombia, the need to develop legal strategies to restore and repair the environmental impacts of the IAC has been highlighted (Pérez-Rincón et al. 2022). Furthermore, ER has recently been incorporated into peace-building policies. Examples include its inclusion in judgments for the restitution of territorial rights for ethnic communities, collective reparations for victims of the IAC, restorative justice processes, projects led by the Colombian Armed Forces, and jurisprudence enabling social service for peace (Molina-Orjuela et al. 2022; Unidad para la Atención y Reparación Integral a las Víctimas [UARIV] 2024; Jurisdicción Especial para la Paz [JEP] 2024).

This is particularly relevant since it has been shown that ER in programs can be highly costly (Andres et al. 2024) and in highly conflictive territories it may be unfeasible due to security concerns (Bruch et al. 2023). Therefore, prioritization models can help to better focus resources (Méndez-Toribio et al. 2017) and guide restoration processes by incorporating socio-environmental interpretations of conflict into the assessment (Bruch et al. 2023), ensuring not only degraded ecosystems recovery, but also contribution to human wellbeing (Nelson et al 2024).

In addition, a significant proportion of studies on restoration prioritization rely on technical approaches that tend to exclude cultural, affective and political dimensions (Castillo-Madujano and Smith-Ramírez 2022; Teshager and Soromesa 2025;). For this reason, studies such as Ocampo Melgar et al. (2016); Dos Santos et al. (2020); Rabêlo Costa et al. (2021) and Corderio et al. (2022) recommend transdisciplinary approaches, moving beyond exclusively ecological focus.

In the Colombian context, despite advances in prioritization of areas for restoration led by the Ministerio de Ambiente y Desarrollo Sostenible [MADS] (2023) and the Alexander von Humboldt Biological Resources Research Institute in Viña-Piñeros et al. (2021), these do not incorporate impacts of war as a socio-ecological disturbance, nor as a driver of ecosystem transformation, they also do not take social variables into account, and do not capture the complexity of more than five decades of the IAC or the emerging war dynamics of the post-conflict period.

For this reason and given the high levels of uncertainty and the complexity of socio-ecological systems in conflict-affected territories, fuzzy logic appears as a suitable methodological approach (Adriaenssens et al. 2004). This artificial intelligence tool integrated with spatial modeling has proven to be an appropriate approach for modeling complex phenomena, especially when the variables involved exhibit high levels of uncertainty, imprecision, or spatial and temporal variability (Ibeh et al. 2025). Its application is especially useful for ER in scenarios where environmental and social conditions are constantly changing or may be ambiguous (Ocampo-Melgar 2016).

For this purpose, this study aims to identify priority ER scenarios in IAC affected territories in Colombia, through the integration of fuzzy logic modeling and Geographic Information Systems (GIS). Thus, this proposal explicitly addresses the inherent uncertainty of complex socio-ecological systems, through a conceptual model that articulates biophysical and social dimensions to understand the impacts of the IAC as a disturbance. The main outcome is the identification of five prioritization scenarios that can contribute to the design of ER strategies adapted to the conditions of territorial conflict.

Materials and methods

1. Selection of prioritization criteria

To select the prioritization criteria, a literature review was first conducted using databases including Dialnet, ProQuest (Social Science Database and Criminal Justice), Google Scholar, ScienceDirect, and Web of Science, with the aim of analyzing the relationship between war, understood as a socio-ecological disturbance, and ER in post-conflict contexts. Additionally, institutional sources such as territorial restitution rulings and reports from the JEP, the CNMH and the Comision de la Verdad (Colombia's Truth Commission) were incorporated in order to contextualize the historical, political, and socio-environmental dimensions of the Colombian armed conflict. Based on these sources, a matrix was developed linking each reference to its conceptual, relational, and causal contributions, aimed to identify the consequences of war on the environment and the integration of restoration into post-war and peacebuilding processes at the global, regional, and national scales (De León-Casillas et al. 2019).

Following this, a conceptual model for Colombia was built from the matrix based on the conservation model proposed by Salafsky (2002) (Fig. 1), focusing on *threats and other factors* and considering the IAC as a structuring factor of biophysical, social, and institutional components. Likewise, the *practitioners* were defined, including both armed and non-armed actors, as well as the *Actions: Approaches*, *strategies*, and *tools*, particularly those derived from national and international organizations oriented toward peacebuilding.

Finally, based on this model, ten criteria were selected which, due to their heterogeneity and the need to integrate ecological and social dimensions, these criteria were grouped using a thematic categorization approach (Table 1). The criteria were used as analytical inputs to evaluate dynamics associated with the IAC in relation to environmental degradation and social vulnerability across territories.

Table 1

Table 1 Categorical, temporal, and measurement characteristics of the criteria selected for ecological restoration prioritization in conflict-affected areas of Colombia

Dimension	Category	Criterion	Historical range	Unit of measurement	Source of information	Range
Biophysical	Biophysical	Ecosystem transformation	2024	Degree of transformation	IDEAM[a]	0–6
		Climate vulnerability	2017	Climate Vulnerability Index by municipality	IDEAM	0–0,324
Socioeconomic	Socioeconomic	Inequality	2023	GINI Index by municipality	IGAC[b]	0–0,987
		Dispossession	2024	Number of ruling processes submitted to the UAEGRTD by municipality	UAEGRTD[c]	0-2854
Socio Ecological	Direct impacts of armed conflict on nature and territory	Bombings	1988–2015	Number of bombing events by municipality	CNMH[d]	0–50
		Landmines and UXO	1944–2025	Number of events by municipality	CNMH	0-1651
		Human bodies found in rivers	1970–2010	Number of bodies per river	Colombia's Truth Commission	0-368
		Glyphosate spraying	1996–2015	Percentage of sprayed hectares within the municipality	Colombia's Truth Commission	0-41.8
	Indirect impacts of armed conflict on nature and territory	Coca crops	2001–2023	Average percentage occupied by coca crops over 23 years in 100 hectares	Ministerio de Justicia y del derecho de Colombia (Ministry of Justice and Law of Colombia)	0-30.5
		Deforestation	1990–2020	Forest loss	IDEAM	1–5

[a] Instituto de Hidrología, Meteorología y Estudios Ambientales; [b] Instituto Geográfico Agustín Codazzi; [c] Unidad Administrativa Especial de Gestión de Restitución de Tierras Despojadas; [d] Centro Nacional de Memoria Histórica

2. Fuzzy logic modeling

The fuzzy logic model was developed using MATLAB software, constructing an independent Fuzzy Inference System (FIS) for each category, integrating the selected input criteria derived from the document analysis. Each criterion was represented using trapezoidal or triangular membership functions, defined according to their nature, the ranges identified in the literature, and the empirical distribution of the data, which allowed the representation of graduality and uncertainty inherent to the modeled phenomena (Zadeh 2009). The criteria were combined within the FIS through *if–then* inference rules based on specialized literature and the relational logic of the conceptual model, generating outputs aimed at identifying ER scenarios in IAC contexts (MathWorks, 2025).

2.1. Fuzzy Inference System (FIS) by category

Biophysical category

The selected criteria capture the degree of ecosystem transformation and susceptibility to climate change as determinants of both the need for and feasibility of ER (Lim 2022; Nelson et al. 2024). Ecosystem transformation was operationalized using an ordinal land-cover scale representing progressive levels of anthropogenic modification, modeled with trapezoidal and triangular functions to represent both ranges of full membership and gradual transitions between states. Climate vulnerability, derived from a continuous index, was modeled using triangular functions to avoid imposing rigid classification thresholds. The output variable, termed *biophysical priority*, was structured such that the concurrence of high climate vulnerability and high ecosystem transformation produced elevated ER priority levels (Fig. 2; S1).

Socioeconomic category

The selected criteria represent structural factors of the IAC with environmental degradation, particularly inequality in land access and territorial dispossession (Ojeda 2016; Molina-Orjuela et al. 2022; CNMH 2014). Inequality was modeled using triangular functions that capture gradual transitions between levels. Dispossession was represented using trapezoidal functions with non-equidistant intervals adjusted to its asymmetric distribution to avoid underestimating affected territories. The inference rules established that the concurrence of high levels of both criteria increases the socioeconomic priority for intervention (Fig. 3; S2).

Direct impacts category

This category captures the immediate consequences of armed actions on the territory, which condition both the urgency and feasibility of ER processes (Machlis and Hanson 2008). All criteria were modeled using trapezoidal functions with non-equidistant intervals, appropriate for representing broad thresholds and skewed distributions. For glyphosate spraying, a scheme that excludes the low category was adopted, consistent with the precautionary principle regarding its cumulative and uncertain impacts (Constitutional Court of Colombia 2021). Similarly, the criterion of human bodies found in rivers was modeled without a low category, recognizing both the inherent severity of the phenomenon and its probable underreporting (Rutas del Conflicto 2018; Guglielmucci 2021). The inference rules were structured under a principle of accumulation: the concurrence of higher levels of impact increases the outputs of direct armed conflict impacts (Fig. 4; S3).

Indirect impacts category

This category represents the mechanisms through which the IAC degrades ecosystems over time through territorial control and the financing of war economies (Lavaux 2004; Rodríguez et al. 2017; Pérez-Rincón et al.

2022). In the Colombian case, deforestation and coca crops constitute the main drivers of ecosystem degradation, while simultaneously reflecting differentiated territorial occupation patterns and modus operandi among opposing armed actors (paramilitary groups and guerrillas). The coca crops criterion was estimated as the average percentage of occupied area over a 23-year period, calculated according to the Sistema Integrado de Monitoreo de Cultivos Ilícitos [SIMCI-UNODC] (2026). The inference rules represented cumulative effects, such that the concurrence of deforestation and coca crops increases the level of indirect impact of the armed conflict, identifying territories with persistent degradation dynamics (Fig. 5; S4).

2.2. Defuzzification method

The modeling was performed using the Mamdani fuzzy inference method, which is widely used in environmental decision-making due to its capacity to incorporate expert knowledge through interpretable linguistic rules (Mamdani and Assilian 1975). This method allows both inputs and outputs to be represented through fuzzy sets, facilitating the aggregation of multiple criteria with different units and scales into a coherent prioritization index. Defuzzification was carried out using the centroid method, which transforms the resulting fuzzy set into a continuous numerical value representing the priority degree of each spatial unit.

3. Spatial modeling and GIS integration

Figure 6 presents a schematic representation of the methodology implemented to integrate the FIS with GIS for spatial modeling.

The base layers obtained from official sources (Table 1) underwent a spatial standardization process to ensure input homogeneity. All vector layers were reprojected to the official MAGNA-SIRGAS Origen Nacional coordinate system (EPSG:9377) and clipped to the official boundary of Colombia. The vector layers were converted to raster format using the *Polygon to Raster* tool, while existing raster layers were resampled using the *Resample* tool. In all cases, a cell size of 100 m was established using the national reference raster as the *Snap Raster*.

The 100 m resolution was selected considering both the scale of the original sources and the standards commonly used in spatial prioritization analyses in Colombia (MADS 2023). This resolution is also consistent with the gradual and territorial nature of armed conflict impacts on ecosystems, whose analysis requires capturing continuous spatial patterns rather than isolated events (Álvarez 2003; Raleigh et al. 2010; Armenteras et al. 2013, 2019).

From the standardized raster, a national point grid with 100 m cells was generated using *Create Fishnet*, assigning criterion values to each centroid through *Extract Multi Values to Points*. To optimize computational capacity, the process was executed by regional blocks north, south, east, and west. The resulting tables by category and region were exported as CSV files and evaluated in MATLAB using the *evalfis* function, which applied each FIS and generated a continuous prioritization index from 0 to 1 for each point (MathWorks 2024).

Priority values were reimported into ArcGIS Pro using *XY Table to Point* and converted to raster format with *Point to Raster*. Regional raster for each category was integrated into a continuous national raster using *Mosaic to New Raster*, obtaining a standardized prioritization product for the entire Colombian territory by category.

4. Scenario identification through a Hierarchical Fuzzy Inference System (HFIS)

To generate the national prioritization map, a Hierarchical Fuzzy Inference System (HFIS) was implemented, integrating the biophysical, socioeconomic, direct impact, and indirect impact prioritization indices as inputs into a second-level system to evaluate total ER priority (Fig. 7). This hierarchical approach reduces the complexity associated with high-dimensional fuzzy systems and has demonstrated utility in complex spatial decision-making processes (Ojha 2019; Ozer et al. 2020). Inference rules were defined to identify areas where accumulated armed conflict impacts converge with unfavorable biophysical and socioeconomic conditions, structuring the output into five linguistic labels, represented by triangular functions (Fig. 7; S5).

The result was a continuous national prioritization raster that integrates the four analytical categories for each 100 m cell. Based on it, five scenarios were delineated through an interpretative process considering the model's spatial patterns, the geographic continuity of prioritized areas, and the predominant conflict dynamics within each territory.

5. Identification of ER strategies by scenario

The identification of ER strategies and enabling conditions for each scenario was based on two main inputs. First, the dominant criteria resulting from the model were analyzed for each scenario, identifying the armed conflict dynamics that determine both the urgency of ecological intervention and the operational constraints on its implementation. Second, the findings were contrasted with current Colombian public policy instruments aimed at territories affected by the IAC, including the Programas de Desarrollo con Enfoque Territorial (PDET; Territorially Focused Development Programs), the Estrategia Nacional de Restauración (Colombia's National Ecological Restoration Strategy) (MADS 2015), the Programa Nacional Integral de Sustitución de Cultivos de Uso Ilícito (PNIS; National Comprehensive Program for the Substitution of Illicit Crops), and the Programa de Desminado Humanitario (Colombia's Humanitarian Demining Program). This comparison made it possible to identify the institutional mechanisms available for each scenario and the enabling conditions that must be addressed prior to ecological intervention.

Results

1. Priority scenarios

The results of the scenarios show the distribution of the areas prioritized for ER, summarized in S6, including the number of municipalities and departments, the most prioritized municipalities and the predominant criteria, this provides a framework for the detailed description of each scenario.

1.1. Caribbean scenario

The Caribbean scenario is characterized by the convergence of indirect impacts of the armed conflict and structural socioeconomic conditions as the main drivers of prioritization. It includes nine municipalities in the departments of Bolívar, Magdalena, and La Guajira, with El Carmen de Bolívar, Zambrano, Santa Marta, and Dibulla the being highest priority ones.

Biophysical conditions show low to moderate climate vulnerability and a predominance of agroecosystems, secondary vegetation, and remnants of fragmented forest. Territorial dispossession is the most influential socioeconomic criterion, with values of 908 and 909 in El Carmen de Bolívar and San Jacinto, respectively, while inequality reaches its maximum in Santa Marta (0.92). Direct impacts are moderate, as antipersonnel landmines and unexploded ordnance (UXO) events are concentrated in El Carmen de Bolívar (524 records), and glyphosate spraying is relevant in María la Baja (2.8% of the sprayed area). Forest loss is relatively homogeneous across municipalities, whereas coca crops increase prioritization in Santa Marta and Riohacha.

This pattern indicates that in the Caribbean region, the conflict has operated as a structural and chronic socio-ecological disturbance, primarily expressed through territorial dispossession and coca crops (Fig. 8; S7)

1.2. Chocó–Magdalena Medio scenario

The Chocó–Magdalena Medio scenario is the second largest comprising 58 municipalities, and exhibits the highest spatial overlap among territorial dispossession, deforestation and bodies found in rivers across all scenarios. It extends from northern Chocó and Antioquia, through southern Córdoba, Bolívar, and Sucre, to the Magdalena Medio region in Santander, Boyacá, and Cundinamarca. The highest priority municipalities include Riosucio, Nuevo Belén de Bajirá, Cáceres, Remedios, and San Luis.

Biophysical conditions show medium to high climate vulnerability in Carmen del Darién and Unguía. Agroecosystems and natural ecosystems coexist in municipalities such as Tierralta, Puerto Libertador, Mutatá, and Ituango, and fragmented forests are prominent in Ituango and Dabeiba. Socioeconomic conditions showed medium to high inequality, with a GINI index of 0.93 in Carepa and 0.91 in Ituango. Territorial dispossession reached its highest values in Nuevo Belén de Bajirá (1,112 cases), Riosucio (1,111), and Turbo (1,049).

Direct impacts are concentrated on specific municipalities. Landmine and UXO events were higher in Ituango (594), Anorí (525), and Tarazá (496). The number of human bodies found in rivers is the highest among all scenarios, with 368 in the Magdalena River, 207 in the Cauca River, and 17 in the Nechí River. Indirect impacts show deforestation concentrated in Riosucio, Carmen del Darién, and Nuevo Belén de Bajirá (Chocó), while coca crops were concentrated in Ituango, Tarazá, Valdivia, Cáceres, and Anorí (Antioquia) with strong spatial overlap between these phenomena which significantly increases prioritization due to indirect impacts.

This pattern indicates that in the Chocó–Magdalena Medio region, the conflict has operated as a high-intensity socio-ecological disturbance with multiple expressions, combining direct armed impacts, illegal economies, legal land uses, and territorial dispossession in a simultaneous and cumulative manner (Fig. 8; S8).

1.3. Catatumbo–Arauca scenario

The Catatumbo–Arauca scenario exhibits the highest values of landmine and UXO events among all scenarios, with all categories ranging from medium to high levels. It is located in the eastern region of the country bordering Venezuela and comprises 19 municipalities in the departments of Arauca and Norte de Santander, with the highest prioritization concentrated in Tibú and Tame.

Biophysical conditions show medium priority, with ecosystem transformation mainly associated with agroecosystems and transitional ecosystems, though Tame and Fortul retain natural ecosystems, while fragmented forests are concentrated in Tibú and Sardinata. Climate vulnerability is low across the entire scenario.

Socioeconomic conditions show critical levels of territorial dispossession, with Tibú registering 2,139 land restitution processes, and inequality reaching a maximum value of 0.84 in Tame.

Direct impacts were the highest among all scenarios, with landmine and UXO events reaching 1,143 in Arauquita, 828 in Tame, and 446 in Tibú. Bombing events showed low to moderate values, with a maximum of seven in Arauquita and four in Tame. Glyphosate spraying is low, affecting 3.8% of the area in Tibú. Human bodies found in rivers are notable in the Catatumbo River (17) and the Casanare River (11). Indirect impacts were also the highest among all scenarios, with widespread deforestation in Norte de Santander and a hotspot between Tame, Puerto Rondón, and Arauquita. Coca crops are concentrated in Tibú, El Tarra, Teorama, and Sardinata.

This pattern indicates that in the Catatumbo–Arauca region, the conflict has operated as a high-intensity socio-ecological disturbance, where both direct and indirect impacts occur simultaneously across the territory (Fig. 8; S9).

1.4. Amazon–Meta scenario

The amazon meta scenario is the largest among all the scenarios and concentrates the highest prioritization in the department of Putumayo, where the highest deforestation rates and direct conflict impacts converge. It includes 45 municipalities across the departments of Caquetá, Cauca, Guaviare, Meta, Nariño, and Putumayo, with high values across all categories in most municipalities, and the highest prioritization is concentrated in San Miguel, Valle del Guamuez, Orito, Leguízamo, Puerto Asís, and Puerto Caicedo.

Biophysical conditions are primarily concentrated in Putumayo, with medium to high climate vulnerability in Leguízamo, Puerto Asís, and Valle del Guamuez. While agroecosystems predominate, extensive areas of natural ecosystems remain in Leguízamo, Mocoa, San Vicente del Caguán, Miraflores, and several municipalities in Meta. Fragmented forests, secondary vegetation, and transformed transitional ecosystems are concentrated in Putumayo, Piamonte, San José del Fragua, Belén de los Andaquíes, and Miraflores. Socioeconomic conditions show territory dispossession as the dominant factor, ranging from 42 processes in Albania to 2,205 in Valle del Guamuez, 1,595 in Mapiripán, and 1,541 in Puerto Guzmán. Inequality reaches maximum values of 0.95 in Leguízamo and Villavicencio.

Unlike the other scenarios, this one presented the highest number of bombing events, with 50 in Puerto Gaitán, 16 in La Macarena, and 12 in Vistahermosa. Landmine and UXO events were also high, with 1,651 in Uribe, 1,000 in Mesetas, and 977 in San Vicente del Caguán. Human bodies found in rivers are recorded in the Caquetá River (8), and in the San Juan and Guaviare rivers (7). Indirect impacts showed high deforestation rates concentrated in Putumayo, Caquetá, Guaviare, and Meta, as well as coca crops in San Miguel, Orito, Valle del Guamuez, Puerto Asís, Puerto Caicedo, Villagarzón, and Ipiales.

This pattern indicates that in the Amazon–Meta region, the conflict has operated as a high-intensity socio-ecological disturbance with broad territorial expression, where direct and indirect impacts occur simultaneously in the country's most forested region (Fig. 8; S10).

1.5. Cauca–Nariño scenario

The Cauca-Nariño scenario stands out for having the highest levels of inequality and glyphosate spraying among all scenarios, with all categories ranging from medium to high values. It includes 18 municipalities across the

departments of Nariño and Cauca, with the highest, with the highest priority in Tumaco, Barbacoas, Roberto Payán, Cumbitara, and Policarpa in Nariño, and El Tambo and Argelia in Cauca.

Biophysical conditions show medium priority with low climate vulnerability throughout the entire scenario. Ecosystem transformation is the most relevant criterion, with a predominance of agroecosystems intermixed with secondary vegetation and fragmented forests in Tumaco, Barbacoas, Samaniego, Cumbitara, Policarpa, and municipalities in Cauca. In contrast, Santa Bárbara, El Charco, Magüí, and Olaya Herrera have natural ecosystems with transformed transitional areas. Socioeconomic conditions are the highest among all scenarios, with critical inequality, as half of the municipalities exceed 0.97 in the Gini index. Dispossession is concentrated in Tumaco (1,882 processes) and El Tambo (944).

Direct impacts do not include significant bombing events, but landmine and UXO events were in ranges from 1,333 in Tumaco to 276 in Argelia and 254 in El Tambo. Glyphosate spraying was the highest among all scenarios, with 10.2% of Tumaco's area affected, followed by Magüí (7.1%), Roberto Payán (6.2%), and El Charco (5.2%). Bodies in rivers are most prominent in the Mira and Patía rivers (9 records each). Indirect impacts followed a similar spatial distribution to direct impacts, showing medium to high values of coca crops and deforestation.

This pattern indicates that in the Cauca–Nariño region, the conflict has operated as a socio-ecological disturbance shaped by structural inequality and territorial control through illegal economies and spraying practices (Fig. 8; S11).

2.

2. **Protected areas and collective territory as ecological refugees**
Protected Areas (PAs) and collective territory (Afro-Colombian community councils and Indigenous reservations) function as strategic axes for ecological restoration, promoting the recovery of degraded ecosystems, strengthening resilience, and supporting both biodiversity and human communities. While PAs primarily modulate biophysical conditions and reduce indirect impacts, collective territory influence inequality and climate vulnerability, modifying restoration priority values.

In the Chocó–Magdalena Medio scenario, the presence of Paramillo National Natural Park reduces restoration priority in municipalities with high inequality, landmine and UXO events, and human bodies in rivers, such as Ituango, Tierralta, and Puerto Libertador (Fig. 9a). Similar patterns were observed in El Carmen and San Vicente de Chucurí (Serranía de los Yariguíes National Natural Park) and in Tame (El Cocuy National Natural Park). Afro-colombian community councils in Riosucio, Nuevo Belén de Bajirá, and Carmen del Darién reduce the priority of indirect impacts and inequality, promoting ecosystem conservation over climate vulnerability and dispossession. In the Amazon–Meta scenario, municipalities such as San Vicente del Caguán, Uribe, Mesetas, Vistahermosa, Puerto Rico, and La Macarena show high impacts from dispossession and bombing events. However, the presence of national parks (Cordillera de los Picachos, Tinigua, and Sierra de la Macarena) maintains areas with low restoration priority. A similar situation is observed in Leguízamo with La Paya National Natural Park (Fig. 9c).

Additionally, in some regions, protected areas and a collective territory coexist and have contributed to safeguarding ecosystems, and have resisted both direct and indirect impacts of the conflict such as in Sierra Nevada de Santa Marta National Natural Park in Caribbean scenario (Fig. 9d) and Catatumbo-Barí National Natural Park in Catatumbo–Arauca scenario (Fig. 9e), the latest particularly critical due to its proximity to Tibú,

one of the municipalities classified almost entirely as high priority. However, in the Cauca–Nariño scenario, municipalities such as Tumaco, Roberto Payán, Barbacoas, Policarpa, Cumbitara, and Samaniego show extensive overlap with afro-colombian community councils, yet high direct and indirect impacts (landmine and UXO, coca crops, deforestation, glyphosate spraying) and inequality persist.

3. Spatial coherence with PDET regions

Overall, a strong spatial coherence is observed between the prioritized scenarios and the PDET regions. This overlap is complete in the Cauca–Nariño scenario and very high in Catatumbo–Arauca, where prioritized areas largely coincide with PDET boundaries. In the Chocó–Magdalena Medio scenario, the correspondence is missing only in some municipalities in the Magdalena Medio region that were prioritized by the HFIS but do not overlap with PDET areas. In the Caribbean scenario, overlap is also partial, with Riohacha being the only municipality that does not coincide with prioritized areas. In the Amazon–Meta scenario, although most prioritized areas align with PDET regions, some municipalities such as Villavicencio, Acacías, Puerto Gaitán, and San Martín do not show overlap (Fig. 8).

Discussion

1. Methodological validation

The selection of criteria and the design of the FIS are consistent with previous applications of fuzzy logic to sustainability problems involving multiple interconnected factors and poorly defined boundaries (Ducey and Larson 1999). The use of triangular and trapezoidal functions made it possible to represent the subjectivity inherent to each criterion and explicitly incorporate expert knowledge, in agreement with Ocampo-Melgar et al. (2016) and Kuzminov et al. (2020), and in contrast to studies using undulating curves (Mejía Aguilar 2021) or bell-shaped functions (Nebot and Mugica 2021). Unlike approaches that reduce researcher interference through the use of maximum, average, and minimum values without specific weights (Dos Santos et al. 2020), the intervals and weights in this study were defined based on specialized literature and governmental reports, consistent with studies recognizing the role of expert knowledge in the construction of fuzzy models (Lourenço et al. 2015). This approach also represents a methodological contribution in itself, given that the potential of fuzzy logic for evaluating and prioritizing ER actions remains poorly explored (Ocampo-Melgar et al. 2016), and the hierarchical and gradual values it produces allow for a better focus of RE project resources on post-conflict actions that are in their initial phases (JEP 2024), in accordance with the proposal by Méndez-Toribio et al. (2017).

The exclusion of cost as a prioritization criterion may be strategically advantageous (Andres et al. 2024), even that many of the prioritized areas lack basic services, access roads, access to supplies, and clarity regarding land tenure as a result of state abandonment (Rodríguez 2021), conditions that in many cases contributed to the emergence of conflict dynamics and territorial control by armed groups (CNMH 2014). This decision differs from national prioritization exercises that incorporate cost-benefit criteria, such as the approach developed by the Alexander von Humboldt Institute (Viña-Piñeros et al. 2021).

2. Conflict as a socio-ecological disturbance

2. Conflict as a socio-ecological disturbance

The prioritization map obtained differs from the National Restoration Strategy developed by the Ministerio de Ambiente y Desarrollo Sostenible (MADS 2023) because both approaches are based on different conceptual frameworks. While the National Restoration Strategy does not incorporate armed conflict as a driver of biodiversity loss (MADS 2024), the present model is grounded in the idea that conflict has operated as a socio-ecological disturbance that reshapes territorial prioritization patterns, consistent with Castro-Núñez et al. (2017). The explicit incorporation of conflict as a disturbance within the conceptual framework proposed by Salafsky et al. (2002) made it possible to generate scenarios not captured by the National Restoration Strategy (ENR). This distinction has important practical implications: failing to acknowledge conflict as a disturbance may lead to unsustainable ER projects (Olowonihi and Osazuwa 2024) and inefficient use of public resources (Aguilar-Garavito et al. 2025), due to incomplete territorial assessments that omit conflict as a central factor in socio-spatial reconfigurations (Ojeda 2016). The results therefore reinforce the idea that natural resource recovery in post-conflict contexts cannot be effective without addressing the structural factors that originated the violence (Olowonihi and Osazuwa 2024).

The obtained scenarios show strong correspondence with the subregions prioritized by Colombia under the PDET, oriented to the territories most affected by violence. This finding is particularly significant because, although the PDETs were defined based on social and political criteria — including poverty, conflict impact, institutional weakness, and illegal economies (Republica de Colombia 2017a), the model proposed here additionally incorporates biophysical variables while still producing similar spatial patterns. This indicates that the model not only reproduces institutional prioritizations but also supports them through a broader socio-ecological perspective.

In this sense, the results empirically support the idea that the Colombian armed conflict has also functioned as a driver of environmental degradation, consistent with Sánchez-Cuervo and Aide (2013), who demonstrated that changes in forest cover were associated with the conflict, and with Le Billon (2001), who proposed a link between war and intensive resource extraction. Thus, one of the contributions of this study is demonstrating, through an integrative model, that territorial prioritization in conflict contexts cannot be separated from the environmental degradation processes to which war has contributed.

3. Protected areas and collective territory as key elements for ER strategies in the post-conflict period

The prioritization scenarios are consistent with the negative association between PAs and deforestation in Colombia (Negret 2020). These territories not only act as barriers facing forest loss but also have high potential to resist the structural drivers of conflict, contribute to carbon storage, and protect areas of high biodiversity (Molina-Parra et al. 2025). However, PAs within the prioritized scenarios show a high number of landmine and UXO events (S12), making it necessary to evaluate whether there is a relationship between restricted access to these territories and limitations on ecosystem transformation.

It should not be overlooked that, as the conflict caused environmental degradation in many territories, in others it favored conservation, for example, forced displacement and land abandonment promoted regeneration processes in the Chocó–Darién and Magdalena–Urabá regions (Sánchez-Cuervo and Aide 2013), also in the Serranía de la Macarena, conflict dynamics kept these territories beyond the reach of development pressures (Negret 2020). This pattern is especially relevant in the current context, as the increase in deforestation recorded after the Peace

Agreement in these same regions (Clerici et al. 2020) shows that such protection was fragile and temporary, reinforcing the urgency of consolidating these territories through ER actions. Consequently, buffer zones and connectivity corridors between protected areas constitute strategic priority spaces, especially in scenarios where humanitarian demining is a prerequisite for access.

Similarly, collective territory belonging to ethnic groups tend to present lower deforestation rates than other forms of land tenure (Negret 2020), consistent with Vélez et al. (2020), who showed that collective land titling among afrodescendant communities in the Pacific region significantly contributed to reducing forest loss by strengthening community rules for land use. However, this is not a rule, the Cauca–Nariño scenario, despite extensive overlap with afro-colombian community councils, high prioritization values are recorded, consistent with the significant barriers faced by indigenous and afro communities in effectively recovering their territories due to bureaucracy, violence, and the prioritization of economic interests (Park and Hunter-Pazár 2025). Ecological Restoration strategies in these territories require strong coordination with ethnic communities.

In some regions where PAs and Indigenous reservations coexist, such as Sierra Nevada de Santa Marta National Natural Park in the Caribbean scenario and Catatumbo-Barí National Natural Park in the Catatumbo–Arauca scenario, socio-ecological systems have resisted conflict impacts while maintaining low prioritization levels. Therefore, these territories are essential for planning large scale ER actions with a landscape approach (Janishevski et al. 2015), although their strengthening requires differentiated governance approaches according to the context of each scenario (Wiegant et al. 2022).

4. Differentiated ER strategies by scenario

Although humanitarian demining is a critical cross-cutting consideration across all five scenarios, it should not delay ER actions but rather proceed in coordination with them, using as starting points protected areas and collective territory which exhibit less degradation and greater potential for ecological connectivity. Table 2 summarizes the strategies and critical considerations for each scenario.

Table 2

Recommended ER strategies for each scenario, articulated with current public policy instruments in Colombia.

Scenario	Dominant conflict dynamic	Critical consideration	ER strategy	Public policy instrument
Caribbean	Coca crops, dispossession, and inequality	Humanitarian demining concentrated in El Carmen de Bolívar and Zambrano	ER of agroecosystems and ecological connectivity articulated with territorial management	[a]PNR, [b]TOAR, [c]PDET, [d]AICMA, [e]PIRC, [f]APPA, [g]TECAM, Land Restitution and Territorial Rights
Chocó-Magdalena Medio	Dispossession, deforestation, and bodies in rivers	Humanitarian demining concentrated in Ituango, Anorí, and Tarazá	Active forest ER and ER with a symbolic approach in rivers, ER of agroecosystems, recovery of mining-affected areas, ER of sacred sites in TC	PDET, TOAR, PNR, AICMA, [h]PNIS, PIRC, APPA, TECAM, and [i]NDFyB, formalization of illegal mining through the Ministry of Mines and Energy of Colombia, Land Restitution and Territorial Rights
Catatumbo-Arauca	Landmine and UXO, coca cultivation, and deforestation	Humanitarian demining — the scenario with the highest density of landmines and UXO events	Passive and active ER articulated with the progress of demining and the substitution of illicit crops	PDET, TOAR, PNR, AICMA, PNIS, PIRC, APPA, TECAM, formalization of illegal mining through the Ministry of Mines and Energy of Colombia
Amazonía-Meta	Bombings, deforestation, and extractive economies	Humanitarian demining concentrated in Uribe, Mesetas, and San Vicente del Caguán	Active forest and connectivity ER, ER of agroecosystems, recovery of mining-affected areas, ER of sacred sites in TC, ER for the substitution of illicit crop	PDET, TOAR, PNR, AICMA, PNIS, PIRC, APPA, TECAM, and NDFyB, formalization of illegal mining through the Ministry of Mines and Energy of Colombia, Land Restitution and Territorial Rights
Nariño-Cauca	Glyphosate spraying, inequality, and landmines and UXO	Humanitarian demining concentrated in Tumaco, Argelia, and El Tambo	Active forest and connectivity ER, ER of agroecosystems, recovery of mining-affected areas, ER of sacred sites in TC, ER for the substitution of illicit crops, and ER with a symbolic approach in rivers	PDET, TOAR, PNR, AICMA, PNIS, PIRC, APPA, TECAM, and NDFyB, formalization of illegal mining through the Ministry of Mines and Energy of Colombia, Land Restitution and Territorial Rights

[a] Plan Nacional de Restauración (National Restoration Plan); [b] Trabajos, Obras y Actividades con contenido Restaurador-Reparador de la JEP (Restorative and Reparative Works and Activities of the JEP);[c] Programas de Desarrollo con Enfoque Territorial (Territorially Focused Development Programs); [d] Acción Integral Contra Minas Antipersonal (Comprehensive Action Against Antipersonnel Landmines); [e] Planes Integrales de Reparación Colectiva (Comprehensive Collective Reparation Plans); [f] Áreas de Protección para la Producción de Alimentos (APPA; Food Production Protection Areas); [g] Territorios Campesinos Agroalimentarios (Peasant Agri-food

Territories); [h] Programa de Sustitución Voluntaria de Cultivos Ilícitos (National Comprehensive Program for the Substitution of Illicit Crops); [i] Núcleos de Desarrollo Forestal y de la Biodiversidad (Forestry and Biodiversity Development Hubs).

The heterogeneity of socio-ecological disturbances identified among the scenarios, and even within each of them, determines that ER strategies must be strongly territorialized. Although the scenarios coincide with territories previously identified as priorities due to their climate vulnerability and conflict impacts (Aguilar-Garavito et al. 2017), prioritization within each scenario responds to distinct dynamics requiring flexible strategies capable of simultaneously restoring ecological resilience and the functionality of human and natural systems.

In the Amazon–Meta scenario, differentiated patterns of violence and environmental degradation are evident. Municipalities such as Puerto Gaitán, La Macarena, and Vistahermosa concentrate bombing events, whereas Tarazá and Valle del Guamuez register higher glyphosate spraying rates. In Putumayo and parts of Guaviare and Meta, deforestation overlaps with coca crops, while in San Vicente del Caguán and San José del Guaviare it responds to extractive economies and agricultural expansion. In these contexts, the RE must combine actions to negotiate with illegal economies and restore ecological integrity, while coordinating with mining formalization initiatives (Ministerio de Minas y Energía 2026) and models such as the one proposed by Veiga and Marshall (2019) and Prato et al. (2025) especially in regions such as the Caribbean and Amazon–Meta that still preserve extensive natural areas.

A critical issue is that some scenarios are prioritized due to the presence of coca crops within indigenous reserves, as observed in Riohacha and Santa Marta. In these cases, it is necessary to acknowledge that coca cultivation is legal when associated with traditional and spiritual uses among indigenous peoples (Corte Constitutional de Colombia 2018), therefore, RE actions must be coordinated with other actors involved in territorial management and primarily focus on improving socioeconomic and territorial conditions rather than directly intervening in agroecosystems.

In the Catatumbo–Arauca and Cauca–Nariño scenarios, and particularly in Putumayo within the Amazon–Meta scenario, deforestation overlaps with coca crops, high concentrations of landmine and UXO events, glyphosate spraying, dispossession, and inequality. These territories require strong institutional and community coordination to handle the multiple pressures associated with conflict, including the advancement of humanitarian demining, since prioritized municipalities remain outside the national program (Acción Integral Contra Minas Antipersonal (AICMA) (2026), as well as the consolidation of alternatives to illegal economies promoted through the PNIS (Peace Agreement Implementation Unit (Republica de Colombia, 2017b). It is necessary if considering that some crop substitution processes have failed to achieve substantial socioeconomic transformation (Miguel-López and Alba-Maldonado 2024), while strengthening governance through peasant organizational structures.

Ecological Restoration in territories affected by armed conflict must incorporate the participation of victimized communities at every stage and be articulated with policies of reparation, land restitution, and guarantees of non-repetition. Understanding restoration as a simultaneously biophysical, social, and symbolic process of territorial reconstruction is essential for its long-term sustainability.

Finally, the proposed scenarios should be understood as guiding rather than prescriptive, given that the conflict remains dynamic and requires refinement of analytical scales and ongoing contextual interpretation. Municipalities with the highest prioritization continue to face conflicts that exceed the historical dynamics

analyzed here, imposing severe restrictions on the implementation of ER projects —such as the case in Tibú, Barbacoas, Tumaco, Roberto Payán, and the department of Putumayo, where the identified priority is alarming and the tensions of war persist (Amazon Frontlines 2023; Consejo Danés para Refugiados [DRC] 20252025; Defensoría del Pueblo 2025; Human Rights Watch 2025).

5. Limitations

Prioritization at the national scale made it possible to identify areas consistent with other institutional prioritizations such as the PDETs, however, large-scale analyses tend to homogenize territorial information (Levin 1992). Although deforestation has been widely used as an indicator of war's impacts on ecosystems (Castro-Núñez et al. 2017; Dorondel et al. 2021; Ghosh and Ramesh 2023), the available forest/non-forest data for Colombia constitute a general criterion that does not allow to identify that lost coverage specifically due to factors associated with the conflict, as demonstrated by Negret (2020). Associating deforestation with other legal and illegal economies beyond coca cultivation would require a more detailed assessment, since these dynamics are difficult to spatially trace (Duque et al. 2023; International Crisis Group 2021).

A scale-related phenomenon is the homogeneous behavior of biophysical criteria across nearly all municipalities, which may be due to the definition of membership function intervals or from the difficulty of linking ecological criteria with conflict dynamics at the national scale. At smaller scales, this relationship may be more accurately represented (Armenteras et al. 2013, 2019). The model was not subjected to empirical field validation, a limitation that spatial overlap with the PDETs only partially compensates. Finally, the incorporation of cultural variables, community governance, and territorial perception constitutes a priority line for future development; the flexibility of fuzzy logic would allow these to be incorporated into future versions of the model without substantially increasing its complexity.

Conclusions

This study made it possible to define a set of socio-ecological criteria that recognize the IAC not as an external factor, but as a historical and constitutive disturbance of the Colombian landscape. Fuzzy logic proved to be an appropriate approach for integrating heterogeneous information from different sources and time periods, allowing the incorporation of uncertainty, gradients, and expert knowledge in a context where the boundaries between variables are inherently diffused. The inclusion of criteria related to both direct and indirect conflict impacts showed that, although some of these impacts may not severely affect ecosystem structure and function, they do profoundly transform the relationship between people and their territories, which reinforces the idea that environmental degradation in Colombia is closely linked to the IAC and to its social and territorial expressions.

The application of the model identified five priority scenarios at the national scale where ecosystem transformation, deforestation, and different conflict-related impacts converge; several of these coincide with territories already prioritized by the Colombian State for public investment in violence-affected regions, suggesting a structural relationship between environmental degradation and conflict dynamics. The model showed that prioritization depends not only on biophysical variables, but rather on how social, historical, and violence-related dimensions are integrated into the fuzzy rules, showing that territories affected by conflict require differentiated interpretations, like those applied to other types of disturbances. The national map should not be

understood as a universal prescription, but rather as a guiding tool that must always be interpreted in relation to local contexts and the specific historical trajectories of each territory.

Ecological Restoration in territories affected by the IAC can contribute to reparation processes, provided that it is conceived as a collective, participatory, and adaptive process that goes beyond biophysical recovery and incorporates social, cultural, and territorial dimensions. To achieve this, future research should incorporate variables related to community governance and territorial perception, dimensions that could be integrated through the flexibility of fuzzy logic without substantially increasing the model's complexity and move toward participatory validation exercises with communities that lend local legitimacy to prioritizations. Only in this way can restoration contribute not only to healing ecosystems, but also to restoring the relationships between people and their territories.

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References

1. Acción Integral Contra Minas Antipersonal (AICMA) (2026) Portal institucional. Consejería Comisionada de Paz, Bogotá. Accessed 1 June 2026. https://www.accioncontraminas.gov.co/
2. Aguilar-Garavito M, Isaacs-Cubides P, Pena-González N, Warren-Thomas E (2025) Challenges for policy and practice in meeting ambitious ecological restoration targets by 2030: a perspective from Colombia. Biol Conserv 302:110973. 10.1016/j.biocon.2025.110973
3. Aguilar-Garavito M, Schlesinger S, Ramírez W, Hernández AM, Franco-Morales A (2017) La restauración ecológica. In Biodiversidad 2016. Estado y tendencias de la biodiversidad continental de Colombia. Instituto de Investigación de Recursos Biológicos Alexander von Humboldt, pp 45–46. 10.21068/B001.2016.405
4. Adriaenssens V, de Baets B, Goethals PLM, de Pauw N (2004) Fuzzy rule-based models for decision support in ecosystem management. Sci Total Environ 319(1–3):1–12. 10.1016/S0048-9697(03)00433-9
5. Almassi B (2017) Ecological restorations as practices of moral repair. Ethics Environ 22(1):19–40. 10.2979/ethicsenviro.22.1.02
6. Álvarez MD (2003) Forests in the time of violence. J Sustainable Forestry 16(3–4):47–68. 10.1300/J091v16n03_03
7. Amazon Frontlines (2023) La guerra regresa al Putumayo de Colombia, amenazando la supervivencia indígena. https://amazonfrontlines.org/es/chronicles/la-guerra-regresa-al-putumayo-de-colombia-amenazando-la-supervivencia-indigena/
8. Andres SE, Mills CH, Gallagher RV, Adams VM (2024) A framework for ecological restoration cost accounting across context and scale. Biol Conserv 295:110671. 10.1016/j.biocon.2024.110671
9. Armenteras D, Rodríguez N, Retana J (2013) Landscape dynamics in northwestern Amazonia: an assessment of pastures, fire and illicit crops as drivers of tropical deforestation. PLoS ONE 8(1):e54310. 10.1371/journal.pone.0054310
10. Armenteras D, Schneider L, Dávalos LM (2019) Fires in protected areas reveal unforeseen costs of Colombian peace. Nat Ecol Evol 3(1):20–23. 10.1038/s41559-018-0727-8
11. Badrán F (2023) The signing of the peace agreement in Colombia. Old wine in new skins: implications for national security and organized crime. Trends Organized Crime 27(1):173–196. 10.1007/s12117-023-09497-y
12. Benavides-Ossa YA, Ramírez-Sanabria JI, Castaño-Rubiano N, Feuillet-Hurtado C, Castaño-Villa GJ, Aguirre-Acosta N (2022) Anti-personnel mines affect tree diversity in the Selva de Florencia National Natural Park, Colombia. Parks 28(2). 10.2305/IUCN.CH.2022.PARKS-28-2YBO.en
13. Bruch C, Batra G, Anand A, Chowdhury S, Killian S (2023) Conflict-sensitive conservation: lessons from the Global Environment Facility. Routledge, London. 10.4324/9781003351399
14. Castillo-Mandujano J, Smith-Ramírez C (2022) The need for holistic approach in the identification of priority areas to restore: a review. Restor Ecol 30(8):e13637. 10.1111/rec.13637
15. Castro-Nunez A, Mertz O, Buritica A, Sosa CC, Lee ST (2017) Land related grievances shape tropical forest-cover in areas affected by armed-conflict. Appl Geogr 85:39–50. 10.1016/j.apgeog.2017.05.007
16. Centro Nacional de Memoria Histórica (CNMH) Agencia de los Estados Unidos para el Desarrollo Internacional (USAID), Organización Internacional para las Migraciones (OIM), Universidad Nacional de Colombia (2014) Cátedra Basta Ya. Módulo 2: Orígenes, dinámicas y crecimiento del conflicto armado. CNMH, Bogotá
17. Clerici N, Armenteras D, Kareiva P, Botero R, Ramírez-Delgado JP, Forero-Medina G, Ochoa J, Pedraza C, Schneider L, Lora C, Gómez C, Linares M, Hirashiki C, Biggs D (2020) Deforestation in Colombian protected

areas increased during post-conflict periods. Sci Rep 10(1):1–10. 10.1038/s41598-020-61861-y

18. Consejo Danés para Refugiados (DRC) (2025) Reporte situacional: Impacto de los eventos de conflicto armado en la zona del Catatumbo y en Nariño (junio–agosto 2025). https://reliefweb.int/report/colombia/reporte-situacional-impacto-de-los-eventos-de-conflicto-armado-en-la-zona-del-catatumbo-y-en-narino
19. Cordeiro Ramalho AH, Fiedler NC, dos Santos AR, de Oliveira Peluzio TM, do, Carmo FCA, da Silva EF, Maffioletti FD, Moreira TR, Lacerda LC (2022) Fuzzy logic applied in the prospecting of suitable areas for the establishment of commercial forest plantations. Canadian Journal of Forest Research 52(8):1043–1052. 10.1139/cjfr-2022-0070
20. Corte Constitucional de Colombia (2018) Sentencia T-357/18: Derecho a la diversidad étnica y cultural de comunidades indígenas frente a la comercialización de productos derivados de la hoja de coca (Expediente T-357/18). https://www.corteconstitucional.gov.co/relatoria/2018/t-357-18.htm
21. De León-Casillas CE, Bermonti-Pérez M, Moreno-Torres MA (2020) Guía metodológica para una revisión de literatura sistemática. Revista Salud y Conducta Humana 7(1)
22. Defensoría del Pueblo de Colombia (2025) Defensoría urge atención inmediata para la situación humanitaria en el Catatumbo. https://www.defensoria.gov.co/web/guest/-/defensor%C3%ADa-del-pueblo-urge-atenci%C3%B3n-inmediata-para-situaci%C3%B3n-humanitaria-en-el-catatumbo
23. Dorondel Ș, Șerban S, Tudor M (2021) Ecological restoration in liquid societies: lessons from Eastern Europe. Nat Cult 16(2):86–117. 10.3167/nc.2020.160205
24. Dos Santos AR, Araújo EF, Barros QS, Fernandes MM, Fernandes MRM, Moreira TR, Souza KB, Silva EF, Silva JPM, Santos JS, Billo D, Silva RF, Nascimento GSP, Gandine SMS, Pinheiro AA, Ribeiro WR, Gonçalves MS, Silva SF, Senhorelo AP, Heitor FD, Telles LAA (2020) Fuzzy concept applied in determining potential forest fragments for deployment of a network of ecological corridors in the Brazilian Atlantic Forest. Ecol Ind 115:106423. 10.1016/j.ecolind.2020.106423
25. Ducey MJ, Larson BC (1999) A fuzzy set approach to the problem of sustainability. For Ecol Manag 115:29–40
26. Duque Ossa JE, Santos Mojica JL, Castillo Villareal LG, Martínez Sinties JF (2023) Multicrimen y degradación ambiental en Colombia: prioridades para la seguridad ambiental. In Salamanca Rodríguez EA, Serpa Hernández JA (eds) Seguridad humana y construcción de patria en defensa de la vida. Sello Editorial ESDEG, pp 437–454. 10.25062/9786287602595.16
27. Grima N, Singh SJ (2019) How the end of armed conflicts influence forest cover and subsequently ecosystem services provision? An analysis of four case studies in biodiversity hotspots. Land Use Policy 81:267–275. 10.1016/j.landusepol.2018.10.056
28. Ghosh S, Ramesh C (2023) Guns and roses: forest landscape restoration as a nature-based solution in areas of armed conflict. Nature-based Solutions for Resilient Ecosystems and Societies. Springer, pp 149–162. DOI 10.1007/978-981-15-4712-6_9
29. Guglielmucci A (2021) Necrolandscapes: the political life of mutilated and banished corpses in the rivers of Colombia. J Latin Am Cult Stud 29(4):555–580. 10.1080/13569325.2021.1885356
30. Human Rights Watch (2025) Colombia: los grupos armados someten a las comunidades en Putumayo. https://www.hrw.org/es/news/2025/12/05/colombia-los-grupos-armados-someten-a-las-comunidades-en-putumayo

31. Ibeh L, Kouveliotis K, Unune DR, Cuong NM, Mutai N, Fountis A, Samoylenko S, Pattanaik P, Kumari S, Sambiri BB et al (2025) A novel approach to integrating community knowledge into fuzzy logic-adapted spatial modeling in the analysis of natural resource conflicts. Sustainability 17(5):2315. 10.3390/su17052315
32. International Crisis Group (2021) Bosques caídos: deforestación y conflicto en Colombia. Informe sobre América Latina N°91. https://www.crisisgroup.org/sites/default/files/091-colombia-broken-canopy-spanish.pdf
33. Janishevski L, Santamaria C, Gidda SB, Cooper HD, Brancalion PHS (2015) Ecosystem restoration, protected areas and biodiversity conservation. Unasylva 66:20153
34. Jurisdicción Especial para la Paz (JEP), Bogotá (2024) Sistema restaurativo de la JEP entra en funcionamiento con el proyecto 'Siembras de Vida' en la localidad de Usme en Bogotá. JEP. https://www.jep.gov.co/Sala-de-Prensa/Paginas/-sistema-restaurativo-de-la-jep-entra-en-funcionamiento-con-el-proyecto-siembras-de-vida-en-la-localidad-de-usme-en-bogota.aspx
35. Kuzminov A, Sakharova L, Stryukov M, Zolnikov V (2020) Methods of assessing the effectiveness of reforestation based on the theory of fuzzy sets. IOP Conference Series: Earth and Environmental Science 595:012007. 10.1088/1755 – 1315/595/1/012007
36. Lavaux S (2004) Degradación ambiental y conflictos armados: las conexiones. Documento de Investigación 7. Facultades de Ciencia Política y Relaciones Internacionales, Bogotá
37. Le Billon P (2001) The political ecology of war: natural resources and armed conflicts. Political Geogr 20(5):561–584
38. Levin SA (1992) The problem of pattern and scale in ecology. Ecology 73(6):1943–1967
39. Lim CH, Lim BS, Kim AR, Kim DU, Seol JW, Pi JH, Lee H, Lee CS (2022) Climate change adaptation through ecological restoration. In: [Editor(es)] (ed) Natural Resources Conservation and Advances for Sustainability. Elsevier, pp 151–172. DOI 10.1016/B978-0-12-822976-7.00013 – 2
40. Lourenço RW, Silva DCC, Martins ACG, Sales JCA, Roveda SR, M. M., Roveda JAF (2015) Use of fuzzy systems in the elaboration of an anthropic pressure indicator to evaluate the remaining forest fragments. Environ Earth Sci 74(6):4253–4267. https://doi.org/10.1007/s12665-015-4253-6
41. Mamdani EH, Assilian S (1975) An experiment in linguistic synthesis with a fuzzy logic controller. Int J Man Mach Stud 7(1):1–13. 10.1016/S0020-7373(75)80002-2
42. Machlis GE, Hanson T (2008) Warfare ecology. Bioscience 58(8):729–736
43. MathWorks (2024) evalfis — Evaluate fuzzy inference system. MATLAB Help Center. https://la.mathworks.com/help/fuzzy/mamfis.evalfis.html
44. MathWorks (2025) FIS Tree Block. MATLAB Help Center. https://la.mathworks.com/help/fuzzy/fistreeblock.html
45. Mejía Aguilar S, Rodríguez-Espinosa F (2021) Localización de Zonas Prioritarias de Conservación aplicando lógica difusa. Revista GEOESPACIAL 18:14–35
46. Mendez-Garzón FA, Valánszki I (2020) Environmental armed conflict assessment using satellite imagery. J Environ Geogr 13(3–4):1–14. 10.2478/jengeo-2020-0007
47. Méndez-Toribio M, Martínez-Garza C, Ceccon E, Guariguata MR (2017) Planes actuales de restauración ecológica en Latinoamérica: Avances y omisiones. Revista de Ciencias Ambientales (Trop J Environ Sci) 51:1–30. 10.15359/rca.51 – 2.1

48. Miguez-Lopez FA, Alba-Maldonado JM (2024) Desafíos del programa de sustitución de cultivos ilícitos: el caso del municipio Valle del Guamuez, Colombia. Revista de Investigación. Desarrollo e Innovación 14(1):9–26
49. Ministerio de Ambiente y Desarrollo Sostenible (MADS) (2015) Plan Nacional de Restauración: restauración ecológica, rehabilitación y recuperación de áreas disturbadas. MADS, Bogotá
50. Ministerio de Ambiente y Desarrollo Sostenible (MADS) (2023) Raster Escenarios de Priorización para Restauración
51. Ministerio de Ambiente y Desarrollo Sostenible (2024) Estrategia Nacional de Restauración 2023–2026: Juntos para recuperar la naturaleza perdida. Bogotá D.C., Colombia
52. Ministerio de Minas y Energía (2026) El gobierno apoya la formalización del minero de pequeña escala, al tradicional y de subsistencia y mantiene su convicción en el combate de la extracción ilícita de minerales. Ministerio de Minas y Energía, Bogotá. Accessed 1 June 2026. https://www.minenergia.gov.co/es/sala-de-prensa/noticias-index/el-gobierno-apoya-la-formalizacion-del-minero-de-pequena-escala-al-tradicional-y-de-subsistencia-y-mantiene-su-conviccion-en-el-combate-de-la-extraccion-ilicita-de-minerales/
53. Molina-Orjuela DE, Ospina SGC, Alvarado BOG (2022) Environmental impacts of the Colombian armed conflict and effective remediation actions. Revista Científica Gen José María Córdova 20(40):1087–1103. 10.21830/19006586.1129
54. Molina-Parra LM, Pulido-Valenzuela DK, Fuentes-López HJ, Leal-Lara DD (2025) Ethnic-led forest recovery and conservation in Colombia: a 50-year evaluation using semi-automatic classification in the Tucurinca and Aracataca River Basins. Sustainability 17(10):4650. 10.3390/su17104650
55. Murillo-Sandoval PJ, Gjerdseth E, Correa-Ayram C, Wrathall D, van den Hoek J, Dávalos LM, Kennedy R (2021) No peace for the forest: rapid, widespread land changes in the Andes-Amazon region following the Colombian civil war. Glob Environ Change 69:102283. 10.1016/j.gloenvcha.2021.102283
56. Nail S (2018) Memory and resilience: a two-pronged approach to natural spaces in Colombia's transition to a peaceful society. Urban Forestry Urban Green 31:48–55. 10.1016/j.ufug.2018.01.020
57. Negret PJ (2020) Development, armed conflict and conservation: improving the effectiveness of conservation decisions in conflict hotspots using Colombia as a case study. University of Queensland
58. Nebot À, Mugica F (2021) Forest fire forecasting using fuzzy logic models. Forests 12(8):1005. 10.3390/f12081005
59. Nelson CR, Hallett JG, Romero Montoya AE, Andrade A, Besacier C, Boerger V, Bouazza K, Chazdon R, Cohen-Shacham E, Danano D, Diederichsen A, Fernandez Y, Gann GD, Gonzales EK, Gruca M, Guariguata MR, Gutierrez V, Hancock B, Innecken P, Katz SM, McCormick R, Moraes LFD, Murcia C, Nagabhatla N, Pouaty Nzembialela D, Rosado-May FJ, Shaw K, Swiderska K, Vasseur L, Venkataraman R, Walder B, Wang Z, Weidlich EWA Standards of practice to guide ecosystem restoration – a contribution to the United Nations Decade on Ecosystem Restoration 2021–2030. FAO, Rome; SER, Washington DC (2024) IUCN CEM, Gland. 10.4060/cc9106e
60. Ocampo-Melgar A, Valls A, Alloza JA, Bautista S (2016) Fuzzy rule-based decision support system for evaluation of long-established forest restoration projects. Restor Ecol 24:233–241. 10.1111/rec.12325
61. Ojha V, Abraham A, Snášel V (2019) Heuristic design of fuzzy inference systems: a review of three decades of research. Eng Appl Artif Intell 85:916–936. 10.1016/j.engappai.2019.08.010

62. Ojeda D (2016) Los paisajes del despojo: propuestas para un análisis desde las reconfiguraciones socioespaciales. Revista Colombiana de Antropología 52:19–43
63. Olowonihi AP, Osazuwa CM (2024) A conceptual framework to analyse consequences of post-conflict reconstruction interventions. Am J Political Sci Law Criminol 6(9):105–136. 10.37547/tajpslc/Volume06Issue09-09
64. Ozer BC, Mutlu B, Nefeslioglu HA, Sezer EA, Rouai M, Dekayir A, Gokceoglu C (2020) On the use of hierarchical fuzzy inference systems (HFIS) in expert-based landslide susceptibility mapping: the central part of the Rif Mountains (Morocco). Bull Eng Geol Environ 79(3):551–568. 10.1007/s10064-019-01548-5
65. Park A, Hunter-Pazár B (2025) Protecting indigenous and Afro-Colombian rights in post-conflict land restitution: constitutional and international framework failures. Bergen County Academies, USA
66. Pérez-Rincón M, Peralta-Ardila M, Méndez F, Vélez-Torres I (2022) Conflicto armado interno y ambiente en Colombia: análisis desde los conflictos ecológicos, 1960–2016. J Political Ecol 29(1):672–703. 10.2458/jpe.2901
67. Prato AI, Rueda Díaz VC, de Abreu Anunciação A (2025) Key issues for advancing knowledge on ecosystem recovery in post-mining, gas and petroleum areas in Colombia: a systematic review. J Environ Manage [volumen y páginas pendientes]. 10.1016/j.jenvman.2025.003127
68. Prem M, Saavedra S, Vargas JF (2020) Deforestación al final del conflicto: evidencia del acuerdo de paz de Colombia. World Dev 129:104852. 10.1016/j.worlddev.2019.104852
69. Raleigh C, Linke A, Hegre H, Karlsen J (2010) Introducing ACLED: An Armed Conflict Location and Event Dataset. J Peace Res 47(5):651–660. https://doi.org/10.1177/0022343310378914
70. Rabêlo Costa TLS, Mazzochini GG, Oliveira-Filho AT, Ganade G, Carvalho AR, Manhães AP (2021) Priority areas for restoring ecosystem services to enhance human well-being in a dry forest. Restor Ecol 29(5):e13426. 10.1111/rec.13426
71. República de Colombia (2017a) Decreto 893 de 2017, por el cual se crean los Programas de Desarrollo con Enfoque Territorial (PDET). Presidencia de la República, Bogotá. https://www.suin-juriscol.gov.co/viewDocument.asp?ruta=Decretos/30030685
72. República de Colombia (2017b) Decreto 896 de 2017, por el cual se crea el Programa Nacional Integral de Sustitución de Cultivos de Uso Ilícito (PNIS). Presidencia de la República, Bogotá. https://www.suin-juriscol.gov.co/viewDocument.asp?id=30030680
73. Rodríguez D (2021) Abandono estatal, la desgracia del pueblo. Universidad Externado de Colombia – Conexión Externado. https://conexion.uexternado.edu.co/abandono-estatal-la-desgracia-del-pueblo/
74. Rodríguez Garavito C, Rodríguez Franco D, Durán Crane H (2017) La paz ambiental: retos y propuestas para el posacuerdo. Dejusticia, Bogotá. https://www.dejusticia.org
75. Ruiz-Serna Daniel., & Ojeda Ojeda, D. Carolina. (2023). Belicopedia. Ediciones Uniandes
76. Rutas del Conflicto (2018) Más de mil cuerpos recuperados en 190 ríos. Ríos de vida y muerte. Rutas del Conflicto y Consejo de Redacción, Bogotá. Accessed 1 June 2026. https://rutasdelconflicto.com/rios-vida-muerte/especial/mil-cuerpos.html
77. Salafsky N, Margoluis R, Redford KH, Robinson JG (2002) Improving the practice of conservation: a conceptual framework and research agenda for conservation science. Conserv Biol 16(6):1469–1479. 10.1046/j.1523-1739.2002.01232.x

78. Sánchez-Cuervo AM, Aide TM (2013) Consequences of the armed conflict, forced human displacement, and land abandonment on forest cover change in Colombia: a multi-scaled analysis. Ecosystems 16:1052–1070. 10.1007/s10021-013-9667-y
79. Sistema Integrado de Monitoreo de Cultivos Ilícitos (SIMCI-UNODC) (2026) Proyecto SIMCI. UNODC Colombia, Bogotá. Accessed 1 June 2026. https://www.biesimci.org/index.php?id=6
80. Teshager Z, Soromessa T (2025) Geospatial technologies-based priority forest restoration areas identification: a systematic literature review. Preprint Res Square. 10.21203/rs.3.rs-6030089/v1
81. Viña-Piñeros M, Isaacs-Cubides P, Williams B, López-Cubillos S, Schmoeller M, Crouzeilles R, Díaz MC, Ochoa-Quintero JM (2021) Prioridades de restauración en los bosques de un país megadiverso. Instituto de Investigación de Recursos Biológicos Alexander von Humboldt
82. Unidad para la Atención y Reparación Integral a las Víctimas (UARIV) (2024) Registro Único de Víctimas (RUV). UARIV, Bogotá. https://www.unidadvictimas.gov.co/registro-unico-de-victimas-ruv/
83. Veiga MM, Marshall BG (2019) The Colombian artisanal mining sector: formalization is a heavy burden. Extractive Industries Soc 6(1):223–228. 10.1016/j.exis.2018.11.001
84. Vélez MA, Robalino J, Cardenas JC, Paz A, Pacay E (2020) Is collective titling enough to protect forests? Evidence from Afro-descendant communities in the Colombian Pacific region. World Dev 128:104837. 10.1016/j.worlddev.2019.104837
85. Wiegant D, van Oel P, Dewulf A (2022) Scale-sensitive governance in forest and landscape restoration: a systematic review. Reg Envriron Chang 22:25. 10.1007/s10113-022-01889-0
86. Zadeh LA (2009) Fuzzy logic. Springer-, pp 19–49

Figures

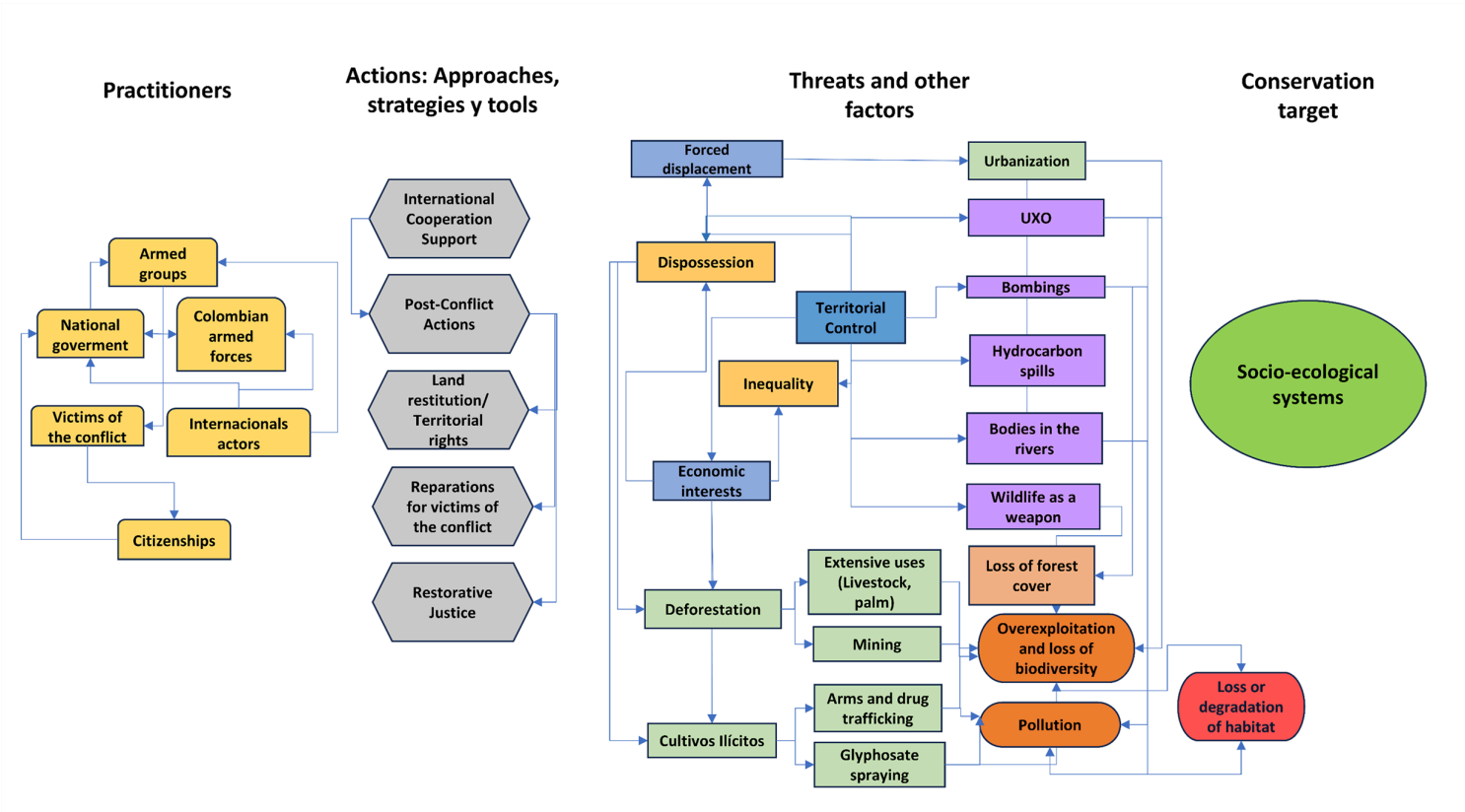


Figure 1

Conceptual framework for Ecological Restoration prioritization in territories affected by armed conflict in Colombia. - UXO: Antipersonnel landmines and unexploded ordnance.

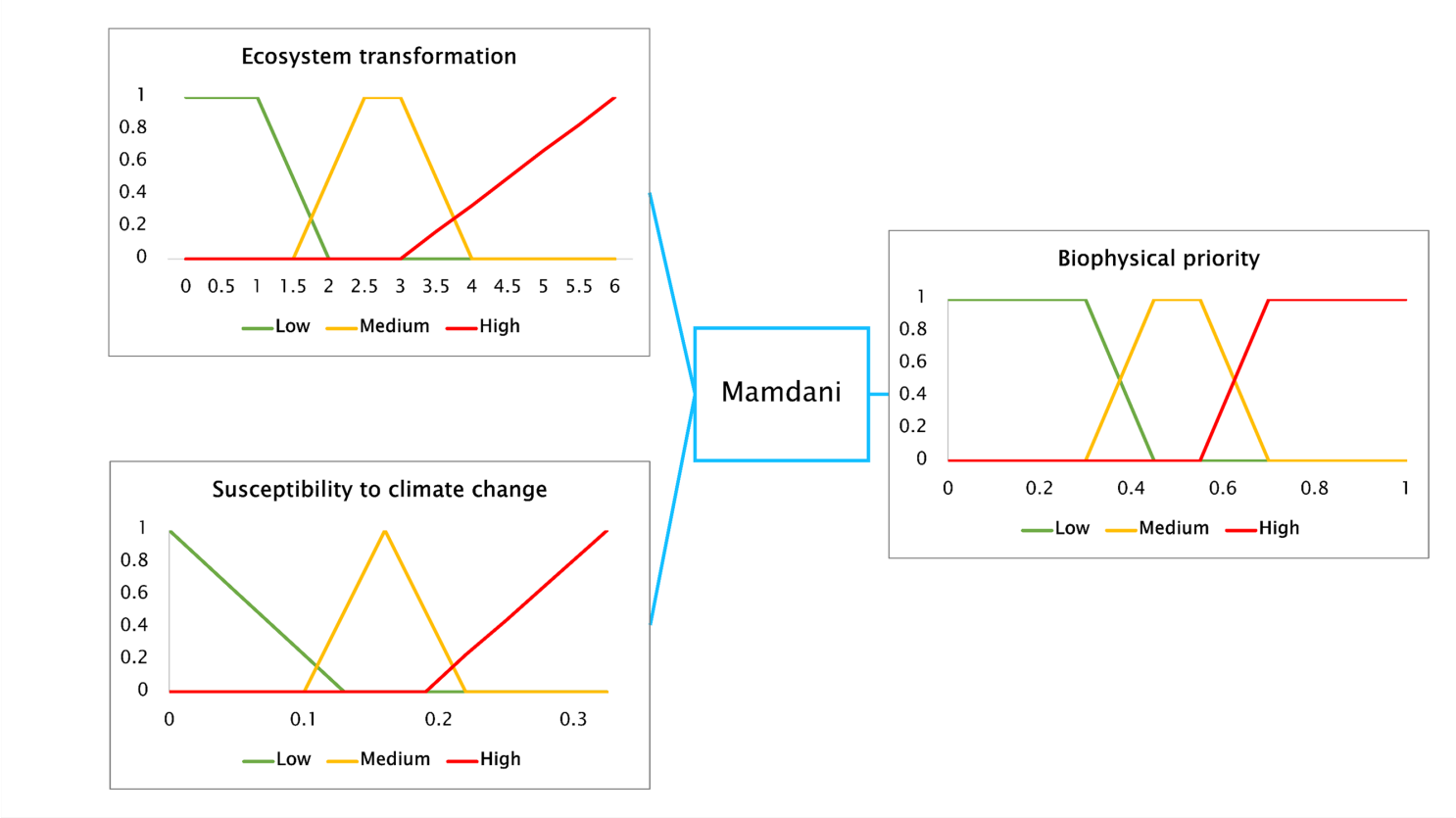


Figure 2

Fuzzy Inference System (FIS) output categories for biophysical conditions in territories affected by armed conflict in Colombia - Ordinal scale of the ecosystem transformation criterion: 0. Natural and no information; 1. Artificialized territory; 2. Artificial water body; 3. Agroecosystems; 4. Transformed transitional areas; 5. Secondary vegetation; 6. Fragmented Forest.

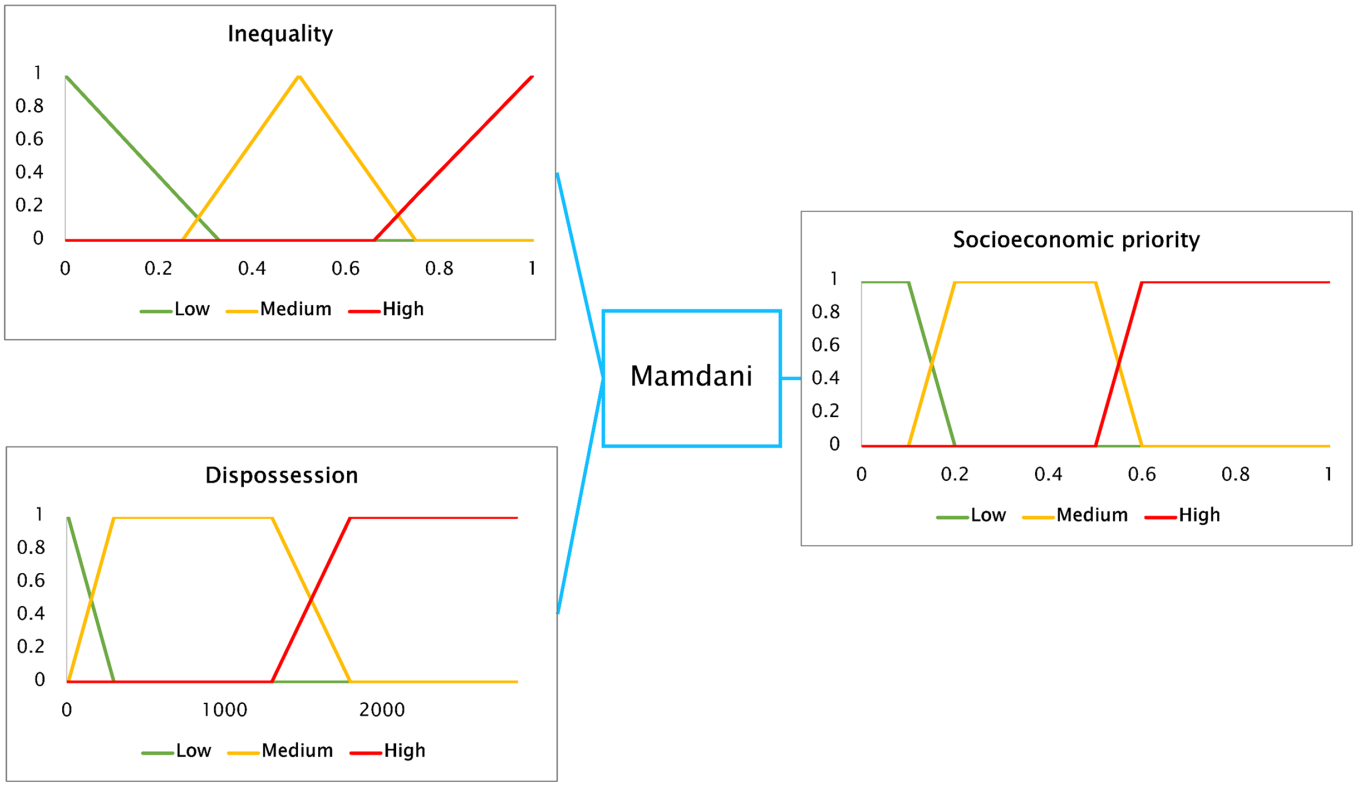


Figure 3

Fuzzy Inference System (FIS) membership functions for socioeconomic condition categories used in Ecological Restoration prioritization

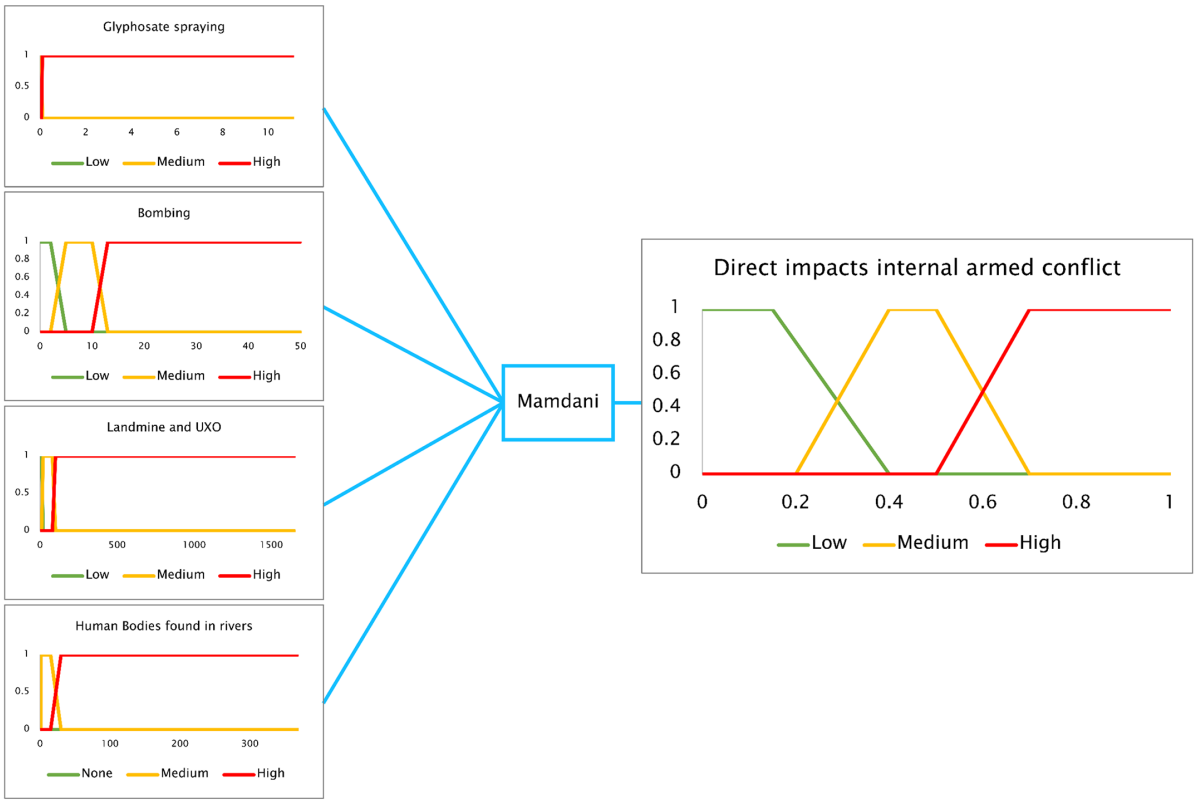


Figure 4

Fuzzy Inference System (FIS) membership functions for direct impact categories used in Ecological Restoration prioritization - UXO: Antipersonnel landmines and unexploded ordnance.

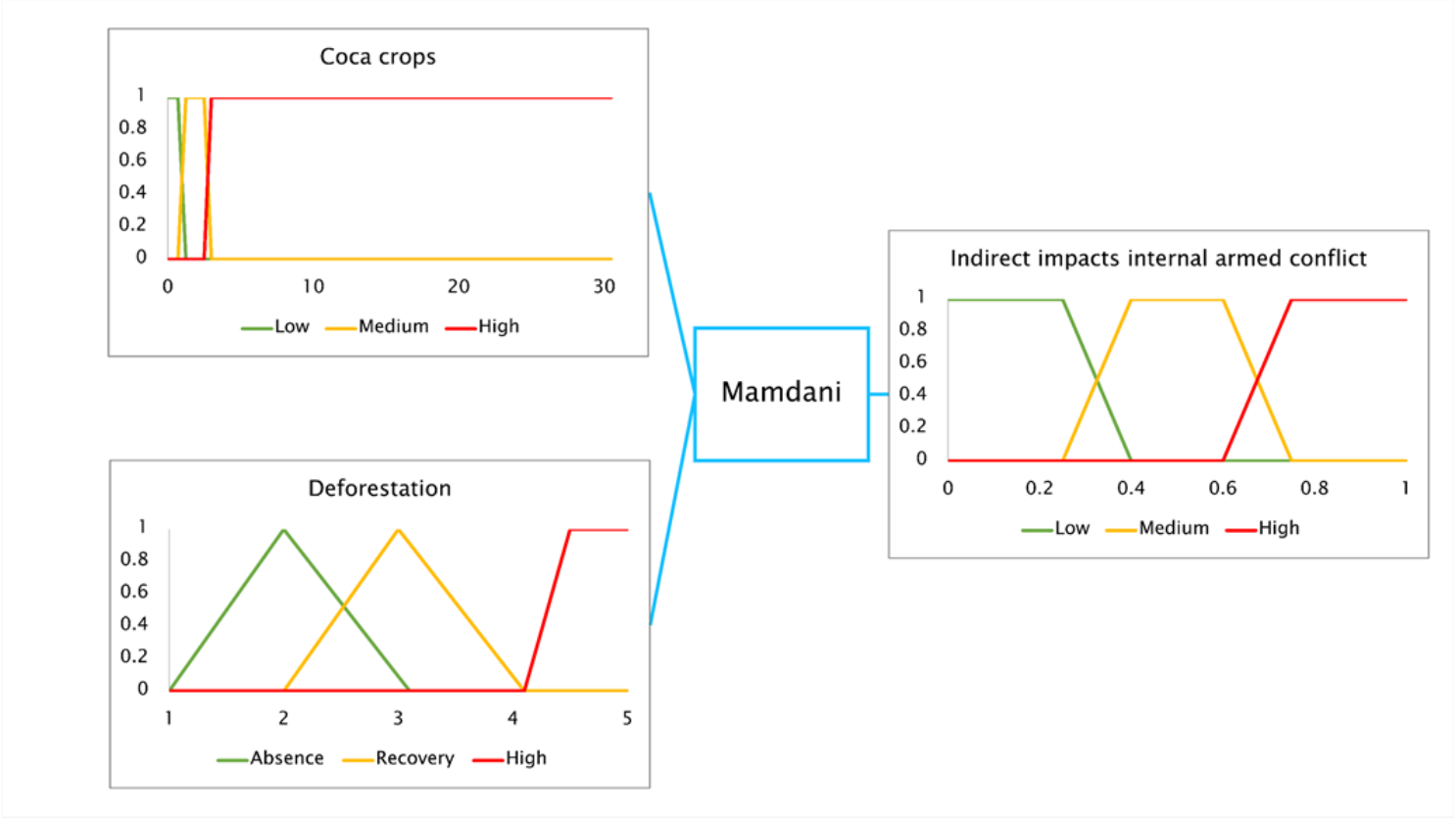


Figure 5

Fuzzy Inference System (FIS) membership functions for indirect impact categories used in Ecological Restoration prioritization - For the deforestation criterion, five land-cover change states were identified: (1) areas with no information, (2) stable forest, (3) forest gain, (4) stable non-forest, and (5) forest loss.

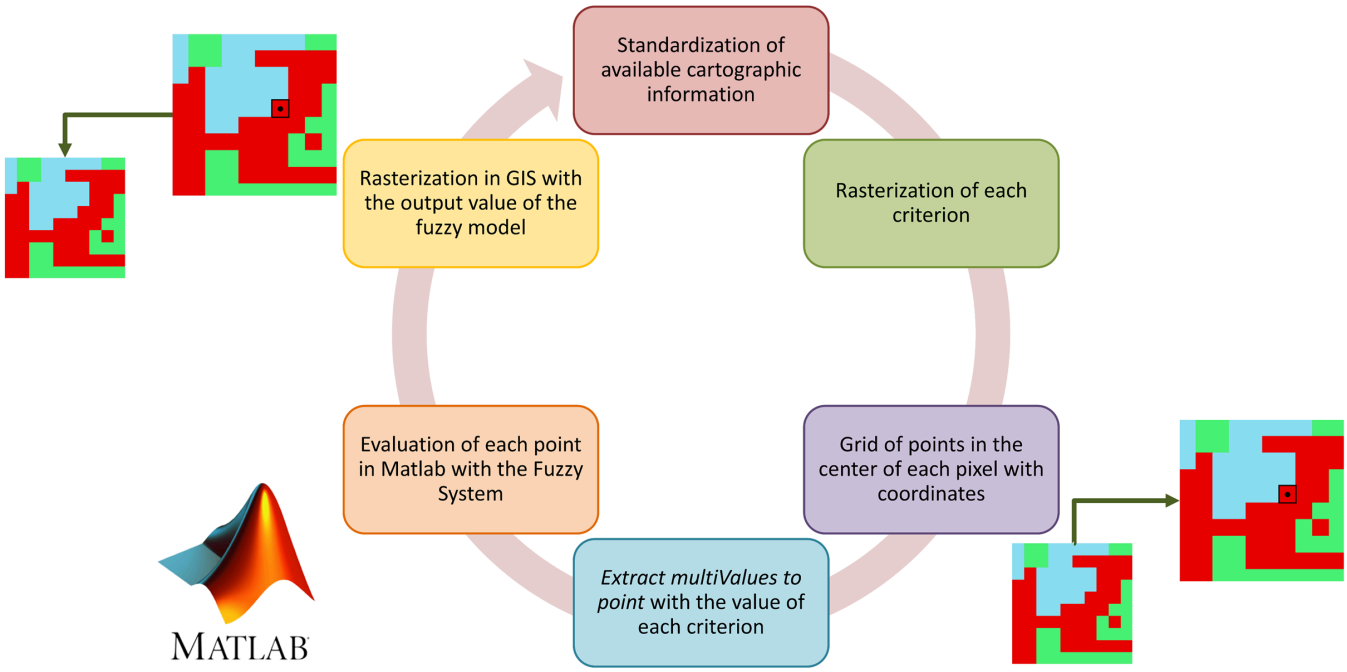


Figure 6

Spatial modeling methodology for Ecological Restoration prioritization through the integration of fuzzy logic and GIS in conflict-affected territories of Colombia

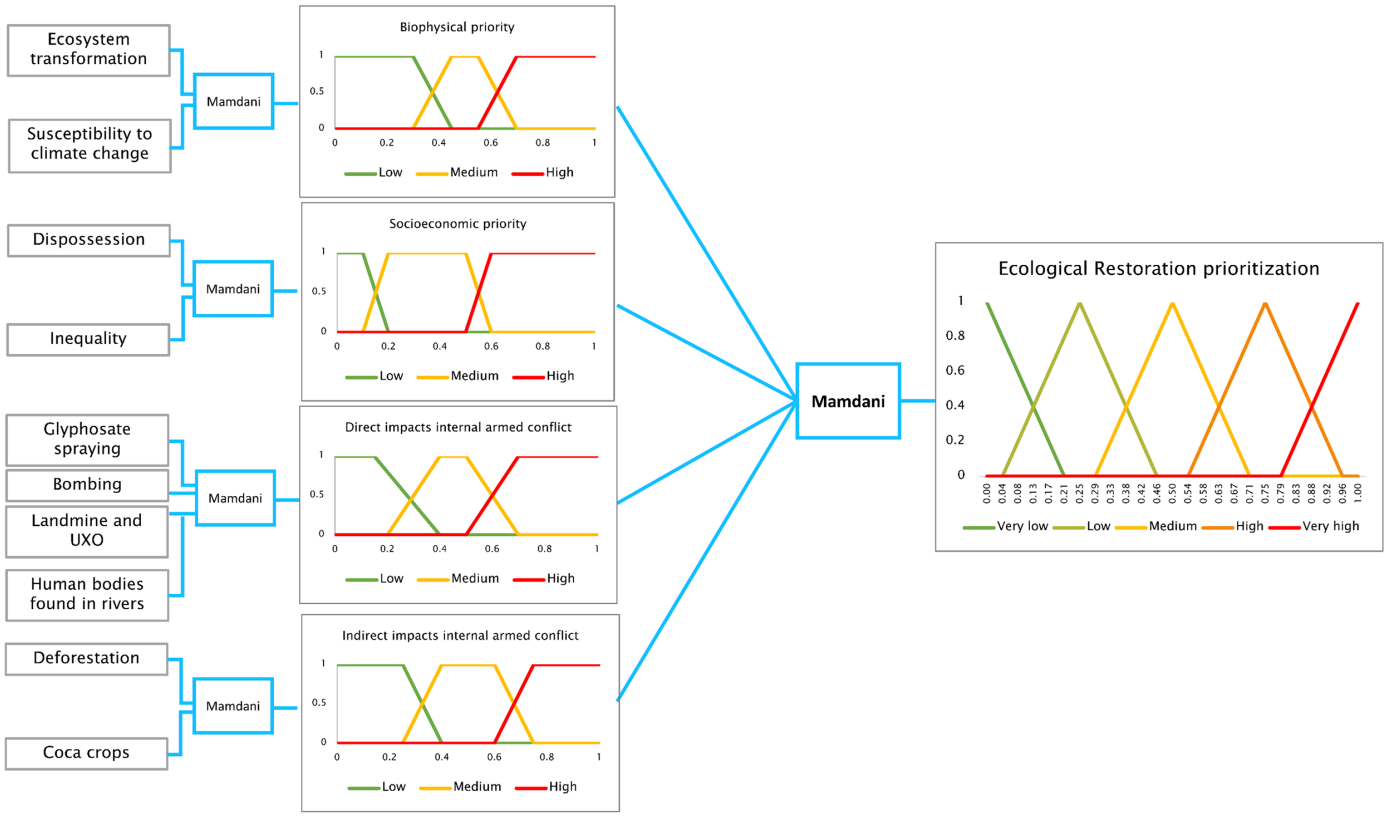


Figure 7

Hierarchical Fuzzy Inference System (HFIS) for Ecological Restoration scenario prioritization in territories affected by armed conflict in Colombia - UXO: Antipersonnel landmines and unexploded ordnance.

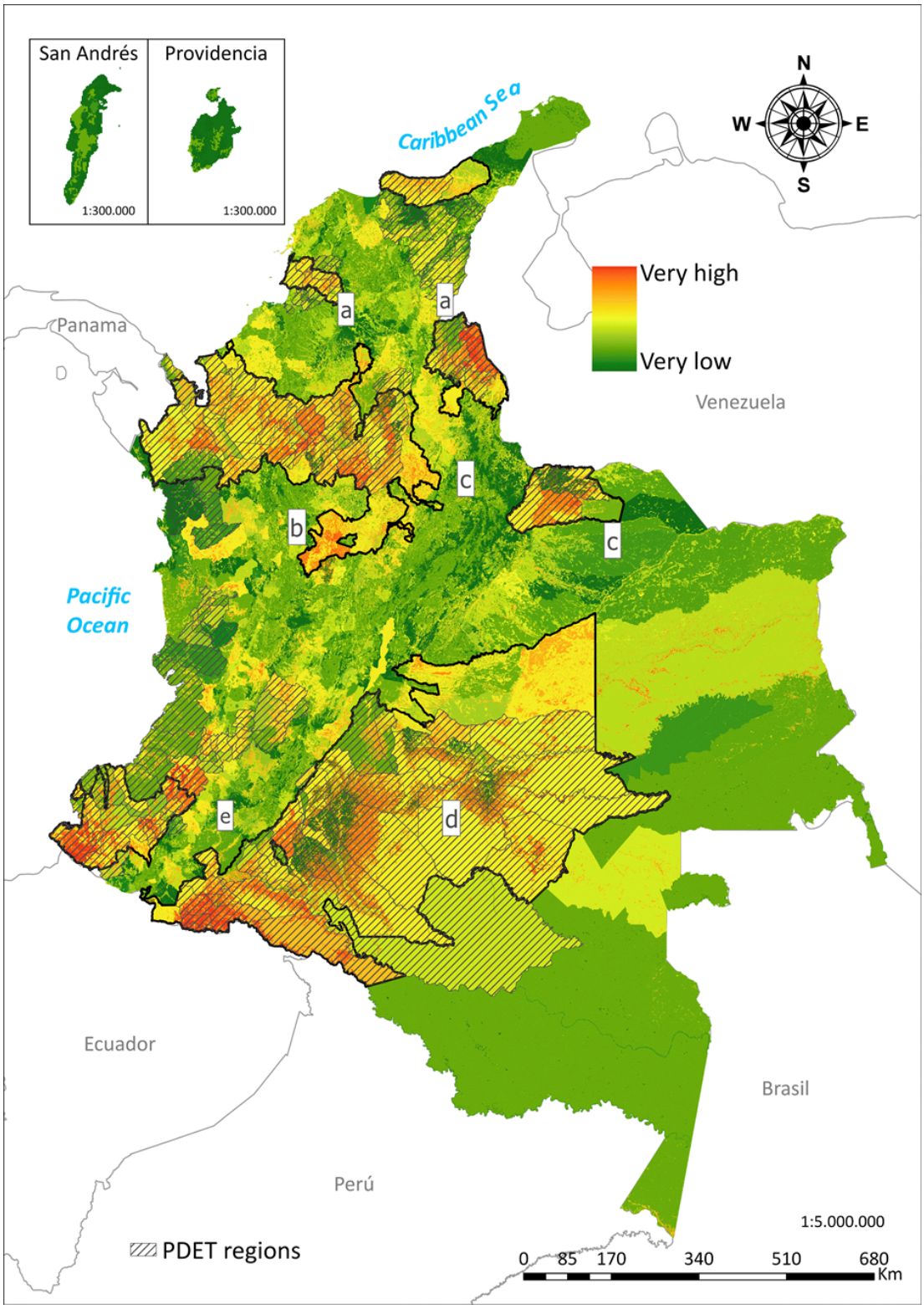


Figure 8

Prioritized Ecological Restoration scenarios and spatial overlap with Territorially Focused Development Programs (PDET) in conflict-affected territories of Colombia; a. Caribbean scenario; b. Chocó–Magdalena Medio scenario; c. Catatumbo–Arauca scenario; d. Amazon–Meta scenario

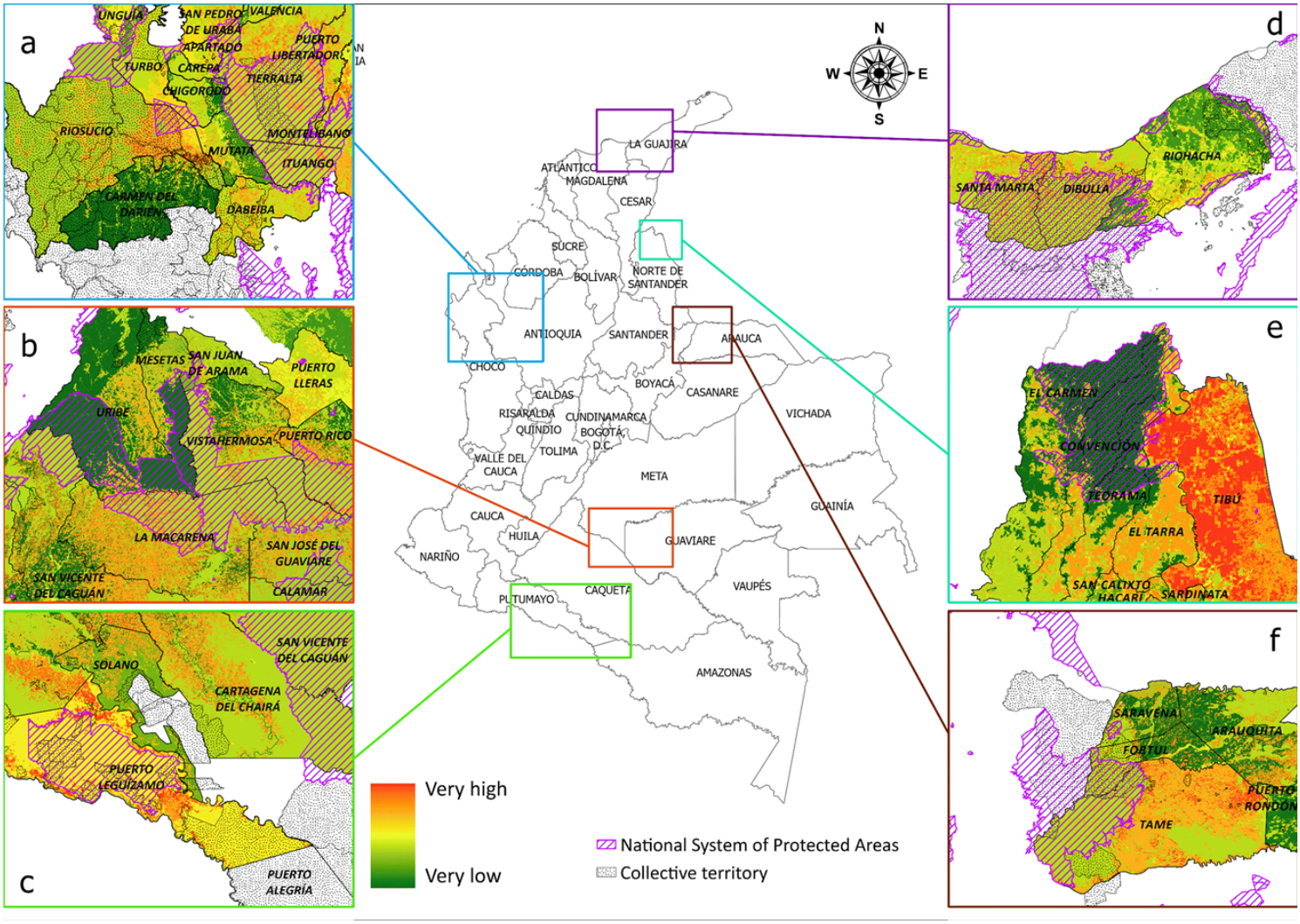


Figure 9

Influence of protected areas and collective territories on Ecological Restoration prioritization in conflict-affected territories of Colombia; a. Paramillo National Natural Park and afro-colombian community councils; b. national parks (Cordillera de los Picachos, Tinigua, and Sierra de la Macarena); c. La Paya National Natural Park and collective territories; d. Santa Marta National Natural Park and Indigenous reservations; e. Catatumbo-Barí National Natural Park and Barí Indigenous reservations; f. Serranía de los Yariguíes National Natural Park and El Cocuy National Natural Park.

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