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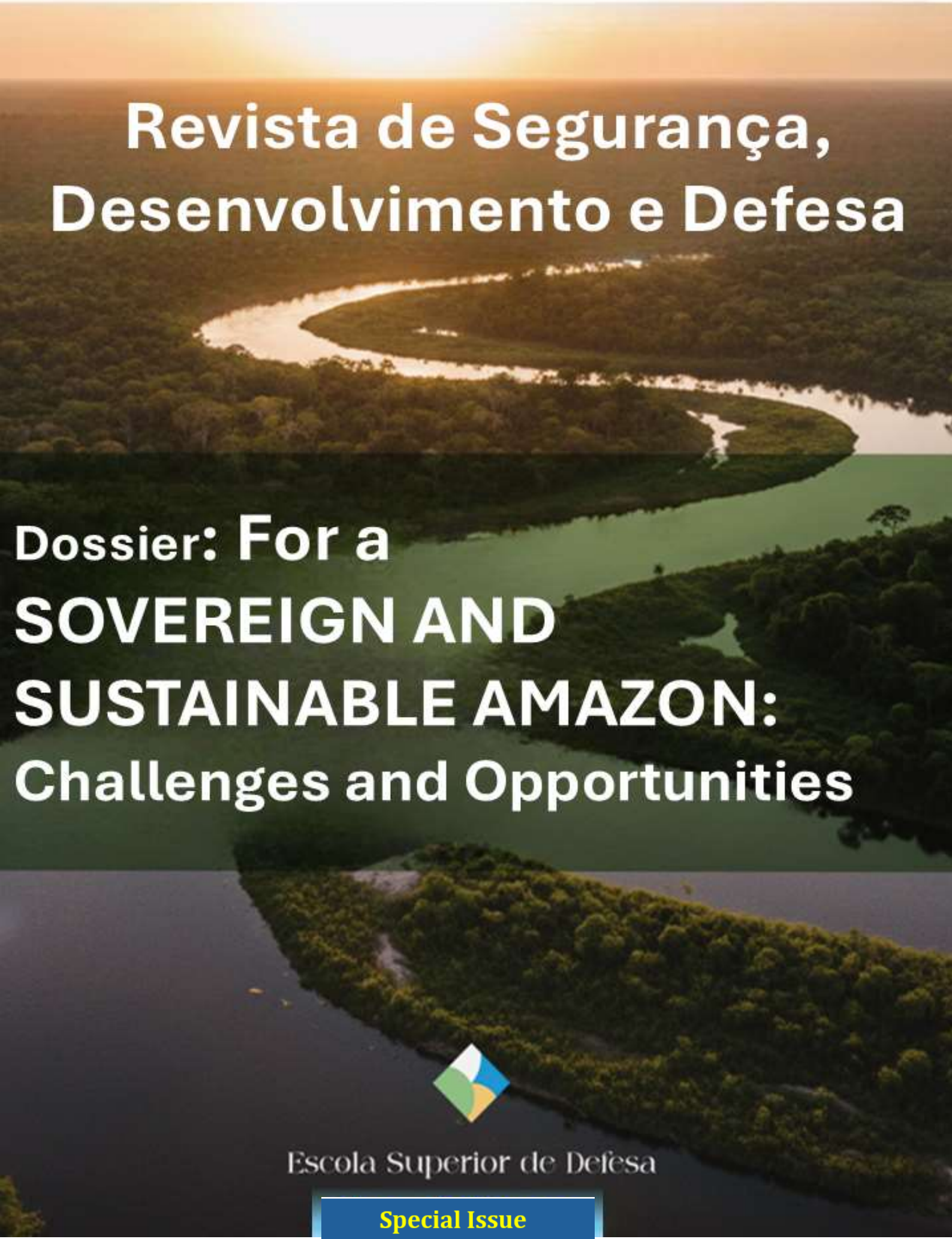

Dossier: For a SOVEREIGN AND SUSTAINABLE AMAZON: Challenges and Opportunities

Escola Superior de Defesa

Special Issue

BRAZILIAN DEFENSE COLLEGE (ESD)
Established on October 1, 2021, by Presidential Decree No. 10,806 of September 23, 2021, the ESD is a higher education institution linked to the Ministry of Defense (MD) that conducts studies, research, outreach, dissemination, teaching, and exchanges on topics of interest to National Defense.

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DOSSIER

For a Sovereign and Sustainable Amazon: Challenges and Opportunities

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FOREWORD

Science and Defense for the Amazon: a convergence between ESD and Censipam

Protecting the Amazon is ensuring our own future. It means recognizing that, within the vast forests, rivers, and skies of this unique region, an extraordinary heritage thrives. The Amazon hosts the world's greatest biodiversity, regulates the climate, stores carbon, and influences the balance of waters and rainfall that sustain agriculture and supply systems throughout the national territory. Defending this wealth is, therefore, a duty of the State and a responsibility shared by all—an ethical, environmental, and strategic commitment to the generations yet to come.

From the perspective of National Defense, the Amazon represents more than a biome: it is a frontier of sovereignty, presence, and integration. The vast Amazonian territory requires constant surveillance, advanced technology, and cooperation among and military institutions to ensure the protection of its populations, natural resources, and critical infrastructure. In this context, the Management and Operational Center for the Amazon Protection System (Censipam) plays an essential role by integrating information, monitoring the territory, and transforming data into strategic knowledge for decision-making.

In a world undergoing constant transformation, scientific knowledge stands as one of the primary instruments of sovereignty, development, and integration among peoples. Publishing this scientific work on the Amazon is far more than gathering articles and studies; it is a concrete expression of Brazil's commitment to truth, to science, and to the sustainable future of its territory.

The launch of this dossier takes place at a particularly timely moment: Brazil is preparing to host COP30, the global climate conference that will place the Amazon at the center of discussions on the planet's environmental future. This context further enhances the relevance of this publication, which emerges aligned with the spirit of the conference – bringing together science, policy, and society around concrete solutions to the climate crisis.

It is, therefore, a strategic contribution that reaffirms the country's role as a regional leader and an active voice in the international environmental agenda.

Each text presented here constitutes a link in the construction of knowledge that guides public policies, strengthens National Defense, and inspires new solutions to complex challenges that transcend borders and academic fields.

Institutions such as the Brazilian Defense College (ESD), in partnership with Censipam, reflect the civilizational value of science. By bringing together civilians and

military personnel in environments of strategic reflection, ESD promotes a culture of defense and critical thinking on security and sovereignty. Censipam, in turn, by transforming data into knowledge applied to territorial and environmental management, converts technology into an instrument of protection, sustainability, and State presence in the Amazon.

The works gathered in this volume address themes that are fundamental to understanding the geopolitics, sustainability, and defense of the Amazon. Among them are the importance of Amazonian strategic hubs, the resurgence of the Amazon Cooperation Treaty Organization (ACTO), perspectives on technological innovation for use in the Blue Amazon—such as SipamMar—the risks posed by transnational organized crime, illegal mining fronts and geospatial alerts, as well as the impacts of climate change on the region.

The policy papers further expand this analysis by addressing strategic issues such as the effects of climate change on security and defense, oil exploration along the Brazilian Equatorial Margin, and the management of recyclable waste within the Brazilian Army.

Guest authors further enrich this volume by reflecting on the sovereign and sustainable management of the Amazon and on Censipam's advances in the context of COP30, reaffirming Brazil's leadership role in science, technology, and sustainability.

By bringing together diverse perspectives – scientific, strategic, and institutional – this publication reaffirms the conviction that the true defense of the Nation begins with knowledge. Protecting the Amazon is protecting Brazil, and strengthening science ensures that this protection rests on solid, ethical, and enduring foundations.

In this sense, ESD and Censipam are honored to share the publication of this thematic dossier.

The value of protecting the Amazon and cultivating science cannot be measured in monetary terms. Both are expressed through sovereignty, solidarity, and hope – manifestations of the country's capacity to unite technology, sensitivity, and human commitment in favor of life. Caring for the Amazon is caring for ourselves; promoting knowledge is preparing for the future. In both gestures lies the essence of what it means to be a Nation: conscious, responsible, and deeply committed to what is essential, vital, and enduring.

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Army General (Reserve)
Director-General of Censipam

CARLA LYRIO MARTINS
Lieutenant General (Medical Corps)
Commander and President
Brazilian Defense College (ESD)

EDITORIAL

Dear Readers,

We are pleased to present, in this issue of the *Revista de Segurança, Desenvolvimento e Defesa* (RSDD), the dossier **"For a Sovereign and Sustainable Amazon: Challenges and Opportunities."** In addition to invited authors, the articles and policy papers were selected through an open call and address challenges and opportunities in defense and security within the unprecedented context of holding the United Nations Climate Change Conference (COP30) in an Amazonian city.

This issue is the result of a partnership between the Brazilian Defense College (ESD) and the Amazon Protection System Management and Operational Center (CENSIPAM), both subordinated to the Ministry of Defense. The works were coordinated by Professor Oscar Medeiros Filho, PhD**,** of ESD, and Edileuza de Melo Nogueira, PhD**,** of Censipam.

The themes addressed in this issue consider the centrality of the Amazon (including the so-called "Blue Amazon") in global climate dynamics, discussing the challenges and opportunities related to the protection and sustainable future of the region. The approach is broad and encompasses topics such as climate change (threats, risks, and vulnerabilities); international and regional cooperation and strategic partnerships for Amazon governance; command-and-control mechanisms; and sustainable development and technologies.

Consistent with the journal's mission, this issue is organized into three sections. The first presents scientific articles covering a wide range of topics, from geopolitics to the impacts of climate change on the Amazon. The second section comprises policy papers of a more prescriptive nature, which discuss implications and offer recommendations on issues related to the theme. The third section consists of essays by authors specially invited to contribute to this dossier.

We hope that the texts published herein contribute to reflection and to the dissemination of ideas on challenges and opportunities in the field of national security in the context of COP30 being held in Brazil.

We wish you an engaging read.

The Editors

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Articles

In this section, readers will find scientific articles that address, in an interdisciplinary manner, themes related to geopolitical and operational issues concerning the sovereign and sustainable protection of our strategic assets.

The topics covered include challenges and opportunities related to the Amazon, with particular emphasis on the importance of its "Strategic Core Areas" and the "resurgence" of the Amazon Cooperation Treaty Organization (ACTO).

The debates are not limited to the "green" Amazon. One of the articles examines the "Blue Amazon" from a Brazilian perspective within the context of South Atlantic geopolitics. Another describes "SipamMar," a Brazilian autonomous system for the detection and modeling of oil spills.

There is also room for discussion of security challenges in the Amazon, through an article that addresses the threat posed by transnational organized crime to the protection and sustainable future of the region. In this context, one of the texts presents a geospatial indicator of mining fronts, developed on the basis of a mining alert system.

As expected in a dossier focused on COP30, this section brings together two articles that address issues related to climate change in the Amazon and its environmental impacts, drawing on data regarding rising temperatures and changes in precipitation patterns in the region.

Geopolitics of Pan-Amazonia: Brazil's role and the transformative power of its strategic hubs*

Geopolítica da Pan-Amazônia: o papel do Brasil e o poder transformador de seus núcleos estratégicos

Geopolítica de la Pan-Amazonía: el papel de Brasil y el poder transformador de sus núcleos estratégicos

Géopolitique de la Pan-Amazonie : le rôle du Brésil et le pouvoir transformateur de ses noyaux stratégiques

Received: 30 May 2025 **Accepted:** 12 August 2025

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*Carlos Alberto Rattmann****

Abstract
Pan-Amazonia is a vast transboundary region.in northern South America. It encompasses areas belonging to nine countries and includes the Amazon Rainforest, which stands out as a strategic zone with significant environmental, social, and geopolitical relevance. This region is notable for its ethnological diversity, abundant water resources, and a wealth of strategically important natural assets, all enriched by unique biodiversity. These characteristics attract the interest of various international actors while simultaneously posing complex transboundary challenges. Therefore, this article primarily aims to analyze the transformative power of Brazil's strategic hubs (industry, academia, and government) as the main drivers for fostering the development of Pan-Amazonia as a whole. The underlying hypothesis is that the strategic articulation among companies, universities, and the Brazilian State is crucial to convert Pan-Amazonia's potential into tangible power for all countries in the region. Brazil is poised to lead this strategic alliance, within the broader concept of the Grand Strategy of the Triple Triad (Góes, 2024), as the key

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to a prosperous future for the region. This exploratory and qualitative research is based on bibliographical sources and official documents, proposing a Pan-Amazonian Grand Strategy under Brazilian leadership.

Keywords: geopolitics, Pan-Amazon, strategic centers.

Resumo

A Pan-Amazônia é uma ampla região transfronteiriça situada na porção norte da América do Sul, englobando áreas pertencentes a nove países e abrangendo a Floresta Amazônica, que emerge como uma zona estratégica, com grande relevância ambiental, social e geopolítica. Essa região se sobressai pela diversidade etnológica, pela abundância de recursos hídricos e pela presença de recursos naturais estratégicos, enriquecida por uma biodiversidade singular. Tais características despertam o interesse de diversos atores internacionais, ao mesmo tempo em que impõem complexos desafios de caráter transfronteiriço. Dessarte, este artigo tem como objetivo principal analisar o poder transformador dos núcleos estratégicos (indústria, academia e governo) do Brasil como os principais vetores para impulsionar o desenvolvimento da Pan-Amazônia como um todo. Nesse sentido, parte da hipótese de que a articulação estratégica entre empresas, universidades e o Estado brasileiro é decisiva para converter o potencial da Pan-Amazônia em poder concreto para todos os países da região. Cabe ao Brasil liderar esta aliança estratégica, no âmbito da concepção mais ampla da *Grande Estratégia da Tríplice Tríade* (Góes, 2024), como a chave para um futuro de prosperidade para a região. Esta pesquisa, exploratória e qualitativa, fundamenta-se em referências bibliográficas e documentos, propondo uma Grande Estratégia Pan-Amazônica sob liderança brasileira.

Palavras-chave: geopolítica, Pan-Amazônia, núcleos estratégicos.

Resumen

La Pan-Amazonía es una amplia región transfronteriza situada en la parte norte de América del Sur, que abarca territorios pertenecientes a nueve países e incluye la Selva Amazónica, la cual se erige como una zona estratégica de gran relevancia ambiental, social y geopolítica. Esta región destaca por su diversidad etnológica, la abundancia de recursos hídricos y la presencia de recursos naturales estratégicos, enriquecida por una biodiversidad singular. Tales características suscitan el interés de diversos actores internacionales, al tiempo que plantean complejos desafíos de carácter transfronterizo. En este sentido, el presente artículo tiene como objetivo principal analizar el poder transformador de los núcleos estratégicos (industria, academia y gobierno) de Brasil como los principales vectores para impulsar el desarrollo de la Pan-Amazonía en su conjunto. Se parte de la hipótesis de que la articulación estratégica entre empresas, universidades y el Estado brasileño es decisiva para convertir el potencial de la Pan-Amazonía en poder concreto para todos los países de la región. Corresponde a Brasil liderar esta alianza estratégica, en el marco de la concepción más amplia de la Gran Estrategia de la Tríplice Tríada (Góes, 2024), como clave para un futuro de prosperidad para la región. Esta investigación, de carácter exploratorio y cualitativo, se fundamenta en referencias bibliográficas y documentos, proponiendo una Gran Estrategia Pan-Amazónica bajo liderazgo brasileño.

Palabras clave: geopolítica, Pan-Amazonía, núcleos estratégicos.

Résumé
La Pan-Amazonie est une vaste région transfrontalière située dans la partie nord de l'Amérique du Sud, englobant des territoires appartenant à neuf pays et comprenant la Forêt amazonienne, qui se présente comme une zone stratégique de grande importance environnementale, sociale et géopolitique. Cette région se distingue par sa diversité ethnologique, l'abondance de ses ressources hydriques et la présence de ressources naturelles stratégiques, enrichie par une biodiversité singulière. Ces caractéristiques suscitent l'intérêt de divers acteurs internationaux, tout en posant de complexes défis de nature transfrontalière. Ainsi, le présent article vise principalement à analyser le pouvoir transformateur des noyaux stratégiques (industrie, université et gouvernement) du Brésil en tant que principaux vecteurs pour stimuler le développement de l'ensemble de la Pan-Amazonie. L'hypothèse de départ est que l'articulation stratégique entre les entreprises, les universités et l'État brésilien est décisive pour convertir le potentiel de la Pan-Amazonie en pouvoir concret pour tous les pays de la région. Il revient au Brésil de diriger cette alliance stratégique, dans le cadre de la conception plus large de la Grande Stratégie de la Triple Triade (Góes, 2024), en tant que clé pour un avenir prospère dans la région. Cette recherche, de nature exploratoire et qualitative, s'appuie sur des références bibliographiques et des documents, et propose une Grande Stratégie pan-amazonienne sous leadership brésilien.

Mots-clés : géopolitique, Pan-Amazonie, noyaux stratégiques.

1 INTRODUCTION

Pan-Amazonia is an extensive region located in the northern portion of South America, encompassing territories belonging to nine countries: Bolivia, Brazil, Colombia, Ecuador, Guyana, Peru, Suriname, Venezuela, and French Guiana (an overseas territory of France). It is the cradle of the world's largest tropical rainforest and the planet's richest reservoir of biodiversity, constituting a geopolitical space endowed with a vast ecological heritage that has yet to be adequately harnessed by the Amazonian countries that share it. Transforming this immense potential—spanning energy resources, environmental/green assets, aquifers, biodiversity, the ancestral knowledge of Indigenous peoples, and natural resources—into tangible power requires coordinated action by the true drivers of development: strategic hubs, namely firms, universities, and Brazilian state institutions, articulated in partnership with their counterparts across the other Amazonian countries.

Indeed, Pan-Amazonia will only be able to fully realize its geopolitical potential if synergistic actions are undertaken by its strategic hubs, whether Brazilian or from the other countries of the region. Innovative firms, universities that generate technological knowledge, and governments acting as financing and regulatory authorities – within each Amazonian nation and in close regional cooperation – will be the transformative actors capable of ensuring a future of development and social well-being for the region and its peoples.

The emergence of the environmental movement between the 1960s and 1970s brought natural resources and the environment to the center of economic, social, and political debates. Its critique of the prevailing development model revealed not merely a tension, but a potential contradiction between economic growth and environmental sustainability (Damasceno *et al*., 2011).

In this context, in 1978, Bolivia, Brazil, Colombia, Ecuador, Guyana, Peru, Suriname, and Venezuela formalized the Amazon Cooperation Treaty with the aim of promoting balanced regional development. The agreement sought to ensure an equitable distribution of economic benefits and to reconcile growth with environmental preservation through multilateral cooperation. In Brazil, the treaty was incorporated into domestic law on 18 August 1980 through Decree No. 85,050, consolidating its status as a significant milestone in environmental diplomacy in the region.

A fundamental concept that emerges in the context of the Treaty is that of Pan-Amazonia, referring to the Amazonian territory shared by the countries that are signatories to the Amazon Cooperation Treaty. This notion goes beyond the purely geographical dimension, encompassing an integrated vision of sustainable development and the cooperative management of natural resources among the participating nations. Such an approach enables an equitable distribution of the benefits arising from this development among them.

From the same perspective, Souza (2014) defines Pan-Amazonia as an idea that:

> [...] arises from the aggregation of all areas belonging to the drainage of the Amazon Basin and characterized by dense, humid forests. However, this concept, which originally derives from natural features, has expanded into the social sphere following the recognition of similar problems that have given rise to territorial conflict, thereby strengthening ethnic-based geopolitics centered on resistance to the socio-environmental impacts of developmentalist policies in the region (Souza, 2014, p. 59).

Pan-Amazonia encompasses the world's largest tropical forest biome and the most extensive hydrographic system on a global scale, covering an area of approximately 7.8 million square kilometers distributed across the territories of nine countries. From a geopolitical and economic standpoint, it is noteworthy that this biogeographical microregion – whose spatial concentration is predominantly within Brazil, which accounts for 67.8% of the total area – confers upon Brazil a position of marked preponderance in the regional context. This contrasts with the participation of other nations, such as Peru, whose Amazonian territorial share is limited to 13% of the total (Penna Filho, 2013).

According to the Ministry of Foreign Affairs of Brazil (2025):

> The Amazon Region is an unavoidable subject in contemporary international debates on natural resources, sustainable development, climate change, and biodiversity. With a population of approximately 38 million people, the Amazon occupies about 40% of South American territory and hosts the world's largest megadiverse forest, serving as the habitat for roughly 20% of all known fauna and flora species. The Amazon Basin contains around 20% of the planet's surface freshwater. The Amazon Hydrological Cycle sustains a complex system of aquifers and groundwater, which may extend over an area of nearly 4 million square kilometers (Brasil, 2025).

Given the strategic importance of the Amazon, the countries that comprise this ecosystem face significant challenges while, simultaneously, encountering substantial opportunities. In this vein, and with the aim of harmonizing and intensifying regional cooperation, the signatory states to the Amazon Cooperation Treaty (ACT) approved, in Caracas, the Protocol of Amendment to the Treaty two decades after its signature. This initiative led to the establishment of the Amazon Cooperation Treaty Organization (ACTO), an international institution endowed with a permanent structure and its own funding (Brasil, 2025).

In December 2002, the Brazilian Government and the Amazon Cooperation Treaty Organization (ACTO) signed an agreement establishing Brasília as the seat of the Organization's Permanent Secretariat. It is noteworthy that, to date, ACTO remains the only multilateral international organization headquartered in Brazil (Brasil, 2025).

For the attainment of the objectives pursued by ACTO member states, the adoption of a strategic-hub culture oriented toward sustainable economic development is indispensable – one that respects environmental preservation while promoting the well-being of local populations. Accordingly, this article seeks to examine how coordination among firms, universities, and state entities in Pan-Amazonia constitutes a necessary condition for consolidating this pan-Amazonian space as a vector of geopolitically relevant power at the regional level, in conformity with the principles of sovereignty, sustainable development, and South American integration.

In fact, building upon the concept of strategic hubs or actors – here conceived as an expansion of the traditional triple helix model (firms, universities/research institutions, and government) – which, acting in full synergy, are expected to promote national development, eliminate poverty and marginalization, and reduce social and regional inequalities within a free, just, and solidaristic society, as set forth in items I to IV of Article 3 of the Federal Constitution.[1]

[1] Thus, *strategic nuclei* are understood as all those actors, entities, companies, or segments—whether private or state-owned, and whether economic, commercial, technological, academic, scientific, financial, regulatory, or industrial—provided that they are capable of participating effectively in international competition under the influence of global production, knowledge, and value chains, with or without investment from the Brazilian State (Góes, 2022, p. 70).

In this context, the consolidation of the Amazon Cooperation Treaty Organization (ACTO) is aligned not only with the provisions of Article 4, sole paragraph, but, more importantly, with Article 3, items I to IV, of the 1988 Constitution (Brasil, 2024). These constitutional provisions establish as objectives of the Federative Republic of Brazil the economic, political, social, and cultural integration of the peoples of Latin America, aimed at the formation of a Latin American community of nations, as well as the foundations of national development anchored in the pursuit of reducing social and regional inequalities, eradicating poverty and marginalization, and promoting a dignified life for all Brazilians.

This means that the formulation of a "Grand Pan-Amazonia Strategy" must provide for synchronized strategic actions by the State aimed at fostering the creation of firms and strengthening universities and research centers in the region. In other words, enhancing the resilience and expansion of the region's triple helix (industry–academia–government) holds the potential to constitute the primary pathway for safeguarding the fundamental rights of Pan-Amazonian Indigenous and riverine populations. In fact, the design of such a strategy may prove crucial to the protection of these communities, which maintain a deep connection to the land and depend upon it for the preservation of their cultural, linguistic, and biological diversity. Ensuring their rights is therefore not only a matter of social justice, but also a strategic necessity for Brazil, including the significant positive gains that its international projection may achieve within the Global Governance System.

Moreover, the strategy has the potential to play a meaningful role in the environmental preservation of Pan-Amazonia, one of the world's richest and most diverse ecosystems, whose protection is vital to global climate regulation and to the overall health of the planet. Its central challenge lies in constructing a strategic archetype capable of identifying an equilibrium between the imperatives of environmental conservation and the region's economic and social development.

Accordingly, in order to harmonize these constitutional values—which place national development and environmental protection in tension—the Grand Pan-Amazonia Strategy should be guided by the principle of *practical concordance*, which presupposes mutual concessions between constitutional provisions of equal normative dignity.

In sum, it should be emphasized that these constitutional precepts constitute a fundamental geopolitical guideline for Brazil's Grand Strategy. Nonetheless, while Latin American integration represents the most promising pathway in the long term, its implementation faces complex structural and political challenges. In this context, the Amazon Cooperation Treaty Organization (ACTO) emerges as a more viable strategic mechanism in the

regional setting, as it focuses on Pan-Amazonia - an area of shared interests and tangible priorities for its member states.

Against this backdrop, it therefore falls to Brazil, as the natural custodian of the largest territorial share of Pan-Amazonia, to assume the mission of conducting this geopolitical orchestra—fine-tuning its Strategic Hubs and synchronizing diplomatic instruments to achieve a successful concert. Ultimately, this situation is distilled into the following aphorism: “Either Brazil assumes its natural leadership in South America, or it becomes geopolitically subordinate to one or more centers of power, particularly China or the United States” (Góes, 2024, p. 38).

2 THE GEOPOLITICS OF PAN-AMAZONIA AND THE CONSTRUCTION OF A BRAZILIAN MULTILATERAL GRAND STRATEGY

From the earliest stages of colonization to the present day, the Amazon has been the object of strategies of economic exploitation and territorial occupation primarily oriented toward meeting exogenous demands. Sovereignty over this region has consistently constituted a crucial element of Brazilian foreign policy, as evidenced as early as the colonial period by the Portuguese expansion beyond the limits established by the Treaty of Tordesillas – a decisive geopolitical movement to secure Lusitanian control over the Amazon Basin (Aguiar Cavalcante, 2025).

From this perspective, the contribution of Bertha Becker (2005) is particularly noteworthy, as her geopolitical approach emphasizes that:

> Geopolitics has always been characterized by the presence of pressures of various kinds, including interventions in the international arena ranging from the most moderate forms to wars and territorial conquests. Initially, these actions identified the State as their fundamental subject, since it was understood as the sole source of power and the exclusive embodiment of politics, and disputes were analyzed only among States. Today, however, geopolitics operates primarily through the power to influence State decision-making regarding the use of territory, given that territorial conquest and colonial domination have become prohibitively costly (Becker, 2005, p. 71).

From the same analytical perspective, Ferreira (2024) positions the Amazon as a structuring axis of national development policies from the standpoint of central power, arguing that:

> The Amazon, more intensively than other regions of Brazil, given its strategic, geopolitical, and environmental significance, has been – and continues to be – the object of multiple government plans aimed at its process of occupation and the use of its territory. These initiatives result from geopolitical planning intended to ensure the effective incorporation of this vast region into the national territory, with the purpose of integrating it into the national economy and encouraging migration (Ferreira, 2024, p. 29).

However, in the formulation of transnational policies for the Brazilian Pan-Amazonian area, there is a discernible predominance of commercial interests and productive economic development over social, environmental, and collective security dimensions (Souza Leite Garcia *et al*., 2024). This strategic region encompasses transboundary water systems, including the international basin of the Amazon River, the *Alter do Chão* Aquifer, lacustrine complexes, and groundwater reserves. It also possesses hydrological logistical infrastructure, with fluvial waterways that are essential for the transportation of people (population mobility), local agricultural production, and natural resources extracted from the territory. Finally, the region stands out for its unique ecological heritage, endowed with terrestrial biomes of global relevance and ecosystems that are fundamental to environmental balance.

In the view of Kourliandsky (2023), interest in the Amazon region has its roots in the sixteenth century:

> The Amazon corresponds to a European imaginary that was subsequently Westernized. This imaginary, although multifaceted, was constructed by Spanish, French, and Portuguese colonizers from the sixteenth century onward. It was later "enriched" by the imperial powers of the nineteenth century and, in contemporary times, by the powers of the G7 and their non-governmental organizations (Kourliandsky, 2024, p. 60).

As early as 1938, Mário Travassos emphasized the need for Brazil to recognize the geographical magnitude of the Amazon region. From this standpoint, Pan-Amazonia – formed by the nine countries that share the Amazon biome, namely Brazil, Bolivia, Colombia, Ecuador, Guyana, Peru, Suriname, Venezuela, and French Guiana – constitutes one of the world's most strategic regions from environmental, economic, cultural, and geopolitical perspectives.

In light of growing international pressure for environmental preservation, combined with internal challenges related to socioeconomic development and regional integration, it becomes indispensable for Brazil to exercise proactive and responsible leadership in the formulation of a multilateral Grand Strategy for Pan-Amazonia.

It is in this vein that this study seeks to underscore the region's geopolitical relevance for Brazil, as well as the need to harmonize environmental preservation with sustainable development and, above all, the urgency of consolidating a multinational grand strategy under Brazilian leadership, with the Amazon Cooperation Treaty Organization (ACTO) serving as the primary institutional platform.

Accordingly, the Amazon Cooperation Treaty Organization (ACTO) presents itself as the most appropriate multilateral mechanism for coordinating convergent interests and mediating tensions among the Amazonian countries. As previously noted, established in 1978

and revitalized in recent years, the Organization possesses the legitimacy and the legal-institutional scope required to host a Pan-Amazonian Grand Strategy capable of articulating environmental, economic, security, and social policies under a framework of shared sovereignty and regional solidarity.

Brazilian leadership within ACTO should not be confined to the defense of national interests; rather, it should assume responsibility for building consensus and designing a long-term strategy that seeks equilibrium between environmental conservation and socioeconomic development. This necessarily entails harmonizing the constitutional principles of promoting national development and protecting the environment through the principle of *practical concordance*, thereby avoiding normative hierarchies and privileging integrative solutions.

Pan-Amazonian integration faces complex challenges, including economic disparities among member countries, political instability, insufficient transportation and communication infrastructure, as well as divergent extraregional geopolitical interests. Nevertheless, the region also offers unique opportunities for scientific cooperation, the development of sustainable value chains, and the recognition and valorization of traditional knowledge.

The coordination of joint research projects on climate change, the sustainable management of natural resources, and food security – combined with professional training programs and digital inclusion initiatives – has the potential to transform Pan-Amazonia into a global laboratory for sustainable development and socio-environmental innovation.

For example, Marine Spatial Planning (MSP), which, according to the theoretical framework advanced by Andrade and Carvalho (2025), is characterized as:

> [...] an internationally recognized tool for the organization and governance of maritime spaces and of the activities – economic or otherwise—conducted within them. As a public process involving the mapping and analysis of maritime areas that encompasses multiple interests, actors, and factors, it constitutes a complex undertaking. Marine Spatial Planning (MSP) is a necessity for the Brazilian State, consistent with the commitments assumed by Brazil before the international community (Andrade; Carvalho, 2025, p. 6).

In light of the growing complexity of global security dynamics and Brazil's strategic role in the sustainable development of the Amazon, the country must implement a multidimensional approach that combines active diplomacy, integrated strategies, and multilevel cooperation among the members of the Amazon Cooperation Treaty Organization (ACTO).

To conclude, in this regard, it is worth highlighting the perspective advanced by Spader (2024) on this issue:

> […] Brazil has implemented public policies across multiple spheres of National Power to promote environmental protection in the Legal Amazon,

> with a view to maintaining territorial sovereignty. These initiatives aim to strengthen environmental governance; increase the State's presence in the North; combat deforestation and illegal mining; promote research and innovation; and ensure the sustainability of the Legal Amazon. Furthermore, multilateral solutions fall within the scope of Brazilian environmental security, wherein the importance of international cooperation in addressing socio-environmental challenges in the region is duly recognized" (Spader, 2024, p. 14).

Pan-Amazonia constitutes a singular geopolitical space in which complex challenges and strategic opportunities intersect, requiring Brazil to exercise proactive and responsible leadership. Such engagement must be guided by national and regional interests, in accordance with constitutional principles and the international commitments undertaken, while reconciling sustainable development with the preservation of the Amazon biome.

3 PAN-AMAZONIA AS A CORE PILLAR OF THE SOUTH AMERICAN TRIAD IN BRAZIL'S GRAND STRATEGY FOR THE TWENTY-FIRST CENTURY

Brazil's positioning within the emerging multipolar order constitutes a fundamental strategic challenge for the country in the twenty-first century. In light of the reconfiguration of global power, two options present themselves: to assume a leading role in shaping this new international architecture or to occupy a peripheral position, acting merely as a spectator within the global context.

Brazil urgently requires a Grand Strategy—a project that goes beyond the National Defense Strategy (END), the National Defense Policy (PND), or isolated economic plans. Such a comprehensive vision must integrate all instruments of national power – political, economic, military, and diplomatic – in order to achieve the nation's permanent objectives, as enshrined in the Constitution of Brazil.

As masterfully articulated by Meira Mattos, Brazil's concept of development is profoundly democratic and rooted in the traditions of Christian philosophy. Far from being confined to mere economic growth, genuine development, to be authentic, must be integral; that is, it must simultaneously promote all people in their fullness and each individual in his or her entirety (Mattos, 1975).

In this sense, in order to examine Pan-Amazonia as one of the pillars of the South American Triad, it is first necessary to understand the foundational bases of the Grand Strategy of the Triple Triad (Góes, 2024), which structures the country's international projection around three interdependent triads—South American, Atlantic, and World Power – within a broader and more integrated vision of Brazil's strategic priorities. These triads reflect Brazil's principal

internal and external challenges on the global stage, as well as its geopolitical ambitions to position itself among the world's five leading powers.

The first strategic axis – **the South American Triad** – posits South America as Brazil's vital space (*Lebensraum*), a fundamental sphere of influence for projecting its power and consolidating its leadership within the new configuration of the postmodern global order. Consequently, the central challenge of Brazil's Grand Strategy lies in the synergistic articulation of South America's three core geopolitical axes: the Amazon Arc, the Andean Pact, and the Southern Cone. Within this tridimensional framework, the possibilities for Brazil's projection toward the Pacific Ocean are likewise examined.

The second structuring dimension of Brazil's Grand Strategy is the **Atlantic Triad**, conceived as a fundamental pillar of national ocean policy. This strategic axis integrates three essential components: the Blue Amazon (Brazil's sovereign maritime area); strategic projection toward West Africa and the Lusophone space, particularly through the Community of Portuguese Language Countries (CPLP); and presence along the Antarctic Front. In parallel with the role of the South American Triad as a vector for expansion toward the Pacific, the Atlantic Triad also incorporates the projection of Brazilian interests toward the Arctic Ocean, thereby completing the spectrum of the country's oceanic engagement.

Thus, on the premise that oceanopolitics represents the maritime dimension of global geopolitics, Brazilian oceanopolitics may be understood as the strategy for employing oceanic spaces as a vector of national development and a means of projecting the power of the Brazilian State.

The third structuring axis – the **World Power Triad** – articulates Brazil's strategic relations with the three principal global power centers: the United States, Europe, and China, without prejudice to relations with other relevant powers such as Russia, India, and Japan. Within this framework, Brazil's full and competitive integration into global value chains—including supply, production, and innovation—requires a tripartite approach that simultaneously engages North American, European, and Asian markets, with particular emphasis on China's dynamism.

As the central axis of this triad of global influence, the imperative stands out to formulate an autonomous Brazilian Grand Strategy, capable of engaging with these hegemonic poles without geopolitical subordination, while preserving national decision-making independence.

The diagram below (Figure 1) outlines the fundamental pillars of Brazil's Grand Strategy for the twenty-first century, with emphasis on the integrated development of the

innovation ecosystem—namely, the productive articulation among the industrial sector, academic institutions, and governmental policies in Brazil

Figure 1 - Brazil's Triple Triad Strategy

Source: Adapted from Góes (2024); free translation by the translator.

According to Góes (2024), Brazil's National Grand Strategy is grounded in three essential premises:

> a) the first premise is that its inherent objectives are the fundamental objectives of the Federative Republic of Brazil, duly codified in the Constitution; that is, the objectives of Brazil's Grand Strategy correspond to those set forth in Article 3, items I to IV, of the 1988 Federal Constitution;
>
> b) the second premise is that the Grand Strategy must be formulated with the inescapable commitment to fulfill the categorical imperative of Brazilian geopolitics: to elevate the Nation to a position of prominence among the world's five leading powers;
>
> c) the third premise is that priority must be given to strategic actions intrinsically linked to Brazil's four major geopolitical archetypes, which confer upon the country the condition of a superpower in the energy, food, environmental, and aquifer domains (Góes, 2024, p. 44–45).

Therefore, the third strategic axis for the twenty-first century is consolidated through the prioritization of national development grounded in four fundamental geopolitical archetypes that project Brazil as an energy superpower, a food superpower, an aquifer superpower, and an environmental superpower (Figure 2).

In this context, Brazil's strategic vocations as a hydrological and environmental superpower are intrinsically linked to the Pan-Amazonian biome integrated into its national territory.

Figure 2 - Foundational Geopolitical Archetypes of Brazil's 21st-Century Grand Strategy

Source: Adapted from Góes (2024); free translation by the translator.

Within this strategic framework, emphasis is placed on applying an expanded conception of the triple helix—firms, universities, and government—as the structuring axis for the creation of regional strategic hubs. The synergistic action of these actors, organized through platforms of regional and transnational cooperation, can foster economic development, technological innovation, and social inclusion, while reducing inequalities and strengthening Latin American integration, as established in Article 3, items I to IV, of the 1988 Federal Constitution of Brazil.

This methodological approach proposes not only the strengthening of local teaching and research institutions and the creation of firms oriented toward the bioeconomy, renewable energy, and environmental services, but also the implementation of public policies capable of safeguarding the rights of traditional and Indigenous communities, whose symbiotic relationship with the forest is essential to the preservation of the knowledge, cultures, and practices that sustain the region's biological and cultural diversity.

Here lies the foundational basis of Pan-Amazonian geopolitics—namely, the articulation of actions by firms, universities, and Amazonian countries oriented toward the challenges of sustainable regional development. To achieve this objective, it is therefore essential to understand the historical process of occupation of this region as one of the pillars underpinning sustainable development in the Amazon.

Brazil, as the largest holder of Amazonian territory and a prominent actor on the international stage, exercises decisive influence in South America. The policies adopted by the

country over time serve not only as references but also as lessons for other nations—either as models to be followed or as cautions regarding potential missteps (Rito, 2024).

In this sense, to secure recognition as an international steward of the Amazon, Brazil must undertake a critical assessment of its historical policies of territorial occupation and regional development, identifying both advances and inherent contradictions in this process. From such an evaluation, it will be possible to derive theoretical and empirical insights capable of underpinning a sustainable governance model adapted to the region's biogeographical and sociocultural complexities.

In sum, to convert its immense potential into real power, it is necessary to formulate a multinational Pan-Amazonian strategy in which the role of the business and industrial sector is crucial for developing high value-added, low environmental-impact value chains. It is therefore urgent to anchor investments in the bioeconomy (pharmaceuticals, cosmetics, bioproducts), as well as in green technologies and environmental services (such as carbon credits), capable of generating wealth directly within the region, creating qualified jobs, and promoting the replacement of deforestation and illegal mining.

In this vein, national and regional firms, supported by strategic actions undertaken by Amazonian states, act as the architects of the transformation of natural resources into globally competitive products, establishing a solid economic base that strengthens the geopolitical position of the Amazonian countries.

Universities and research centers, in turn, constitute the vectors of the knowledge required to uncover and rationally harness Amazonian potential. They are indispensable for mapping biodiversity and ecosystems across the Amazon Arc; developing technologies directly related to regional specificities; and training highly qualified human capital to operate in these emerging sectors of the green economy.

Within a Pan-Amazonian strategic framework, it is imperative to preserve and valorize the traditional knowledge of Indigenous communities by integrating it with innovative, duly patented technological solutions. Such scientific and technological knowledge should be generated through networked cooperation with foreign institutions and counterparts from other Amazonian countries, thereby establishing a robust foundation for the development of new green products.

Similarly, public authorities at all levels—federal, state, and municipal—acting in Pan-Amazonian cooperation, must be capable of formulating and implementing measures within a Pan-Amazonian Grand Strategy oriented toward sustainable development and the protection of the biome. To this end, it is essential to establish attractive regulatory frameworks that

encourage foreign direct investment in the responsible use of natural resources, as well as investment in critical infrastructure, including logistics, communications, clean energy, and sanitation.

It must be acknowledged that genuine transformative capacity derives from the synergy of the Pan-Amazonian triple helix, led by the Brazilian triple helix. The urgent task, therefore, is to convert natural endowments into tangible wealth, consolidate a sustainable forest-based economy as a pillar of national and regional power, and strengthen both sovereignty and the collective bargaining capacity of Amazonian countries in the face of global challenges and external interests.

Ultimately, Pan-Amazonia will only fully realize its potential as a source of strategic power for Brazil and the other Amazonian countries through the determined and coordinated action of their strategic hubs. Innovative firms and start-ups, universities that generate technological knowledge, and governments acting as financiers and regulators are indispensable agents for catalyzing this paradigmatic transformation of the Amazon region. The challenge is undeniably substantial; nonetheless, sustained synergy among enterprises, universities, and state institutions is essential to translate Pan-Amazonia's strategic potential into real power for all countries of the region.

Such a perspective not only consolidates technological autonomy but also projects the Amazonian countries as a cohesive bloc with enhanced resilience to juridical warfare (*lawfare*) perpetrated by external actors. In doing so, it enables the preservation of Pan-Amazonia as a global ecological heritage while, simultaneously, affirming it as a pillar of the region's tangible geopolitical power—particularly that of Brazil.

4 CONCLUSIONS

Pan-Amazonia is, above all, a space of challenges and opportunities that requires Brazil to exercise responsible leadership by articulating national and regional interests in accordance with constitutional principles and international commitments.

The formulation of a Pan-Amazonian Grand Strategy—anchored in the expanded triple helix and operationalized through the Amazon Cooperation Treaty Organization (ACTO)—would enable the construction of collective solutions to the region's environmental, social, and economic challenges, thereby consolidating national sovereignty and enhancing Brazil's international projection within the Global Governance System.

In this sense, harmonizing environmental preservation with socioeconomic development is not merely an ethical and constitutional requirement; it also represents a geopolitical opportunity for Brazilian leadership in one of the most sensitive and strategic issues of the twenty-first century.

For Brazil—whose Legal Amazon accounts for approximately 60% of national territory—Pan-Amazonia constitutes a domain for affirming sovereignty, advancing international projection, and consolidating security and regional integration policies. The growing internationalization of environmental discourse and exogenous interests directed at the region place upon the country the responsibility to lead a strategy that safeguards national and regional sovereignty while upholding global commitments to environmental preservation and sustainable development. This is the paramount challenge facing Brazilian strategists on the horizon to 2050.

The Amazon transcends its environmental significance and assumes the character of a first-order geopolitical asset. Encompassing approximately 7.8 million km² and hosting the world's largest tropical rainforest, this territory plays a decisive role in global climate regulation, biodiversity stocks, and freshwater resources. At the same time, it faces long-standing socioeconomic vulnerabilities, including high poverty rates, social exclusion, and inadequate infrastructure.

As demonstrated, Pan-Amazonia stands among the most strategic territories on the planet, combining unparalleled environmental wealth, traditional peoples, and high-value economic potential—hence its relevance to the realization of the four major geopolitical archetypes that position Brazil as an environmental, energy, food, and aquifer superpower.

Comprising Amazonian territories distributed across nine South American countries, Pan-Amazonia holds environmental, economic, and geopolitical significance that extends beyond regional boundaries to a planetary scale. Heightened international mobilization around Amazon conservation, coupled with structural challenges of integration, development, and security, compels the Amazonian countries—particularly Brazil—to formulate coordinated and effective strategies.

Accordingly, this article has reflected on the region's geopolitical importance for Brazil and has argued for the formulation of a multilateral Grand Strategy under Brazilian leadership, with ACTO serving as the coordinating platform. Drawing on the methodology of strategic hubs—an expansion of the triple helix model—it proposes the creation of synergistic arrangements among firms, universities, and local governments as a means to ensure sustainable development, safeguard social rights, and protect Pan-Amazonia's environmental heritage.

Within this framework, a Pan-Amazonian Grand Strategy led by Brazil is advanced to reconcile socioeconomic development with environmental preservation through multilateral mechanisms and synergies among strategic actors.

Ultimately, a Brazil-led Pan-Amazonian Strategy breaks with the neocolonial logic of primary commodity exportation and advances a geopolitical renewal of the region grounded in archetypes that valorize the resilience of established strategic hubs while catalyzing the creation of new firms, research centers, and state institutions capable of effective insertion and competitiveness in the international system. It follows, therefore, that integrated governance and a balanced relationship between economic use and sustainability are essential to the region's future.

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The resurgence of the Amazon Cooperation Treaty Organization (ACTO): institutional advancements in the promotion of sustainable development policies

O ressurgimento da Organização do Tratado de Cooperação Amazônica (OTCA): o avanço institucional na promoção de políticas de desenvolvimento sustentável

El resurgimiento de la Organización del Tratado de Cooperación Amazónica (OTCA): los Avances institucionales en la promoción de políticas de desarrollo sostenible

La résurgence de l'Organisation du Traité de Coopération Amazonienne (OTCA) : les avancées institutionnelles dans la promotion des politiques de développement durable

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Abstract
Since the Amazon biome is shared by nature, the integration of the South American Amazon is an indispensable prerequisite for integration into the global economy, avoiding isolation and fostering reflection on the political and economic impacts of cooperation, as well as the long-term prospects of this process in a globalized scenario. In other words, it ratifies the institutional resurgence of the Amazon Cooperation Treaty Organization (ACTO) for the construction of a deterrent force aimed at defending strategic areas, under the exclusive responsibility of the Amazon countries. This article aims to present the historical evolution of the Amazon Cooperation Treaty Organization (ACTO) towards policies directed at the sustainable development of the region. Using the historical-deductive method and the systematic literature review methodology through the use of

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primary sources and specialized bibliographic references on the subject, the central analytical assumption is that ACTO has been emerging from its institutional immobility to establish itself as a pillar of Amazon integration via sustainable development, mainly since the signing of the Belém Declaration during the Amazon Summit, in 2023. Consequently, the benefits of integration are multipliers and radiators, with the main objectives being the reduction of regional asymmetries, the construction of a regional identity, and the expansion of economic and social components.

Keywords: Amazon; Amazon Cooperation Treaty Organization; sustainable development; Belém Declaration.

Resumo

Uma vez que o bioma amazônico é compartilhado por natureza, a integração da Amazônia Sul-Americana é pré-requisito indispensável para se integrar à economia mundial, evitando o insulamento e estimulando a reflexão sobre os impactos político-econômicos da cooperação, assim como as perspectivas de longo prazo desse processo num cenário globalizado. Em outros termos, ratifica a retomada institucional da Organização do Tratado de Cooperação Amazônica (OTCA) para a construção de uma força dissuasória que vise defender áreas estratégicas, sob a responsabilidade exclusiva dos países amazônicos. Este artigo tem como objetivo apresentar a evolução histórica da Organização do Tratado de Cooperação Amazônica (OTCA) rumo às políticas direcionadas para o desenvolvimento sustentável da região. Utilizando-se do método histórico-dedutivo e da metodologia de revisão sistemática de literatura, através do emprego de fontes primárias e referências bibliográficas especializadas na temática, o pressuposto analítico central é que a OTCA vem saindo de seu imobilismo institucional para se firmar como sustentáculo da integração amazônica via desenvolvimento sustentável, principalmente a partir da assinatura da Declaração de Belém durante a Cúpula da Amazônia, em 2023. Consequentemente, busca-se reiterar que os benefícios da integração são multiplicadores e irradiadores, tendo como objetivos principais a redução das assimetrias regionais, a construção de uma identidade regional e a ampliação da participação de componentes econômicos e sociais.

Palavras-chave: Amazônia; Organização do Tratado de Cooperação Amazônica; desenvolvimento sustentável; Declaração de Belém.

Resumen

Dado que el bioma amazónico es, por naturaleza, compartido, la integración de la Amazonía sudamericana constituye un requisito indispensable para su inserción en la economía mundial, evitando el aislamiento y fomentando la reflexión sobre los impactos político-económicos de la cooperación, así como sobre las perspectivas a largo plazo de este proceso en un escenario globalizado. En otros términos, se ratifica la reactivación

institucional de la Organización del Tratado de Cooperación Amazónica (OTCA) para la construcción de una fuerza disuasoria destinada a defender áreas estratégicas, bajo la responsabilidad exclusiva de los países amazónicos. Este artículo tiene como objetivo presentar la evolución histórica de la Organización del Tratado de Cooperación Amazónica (OTCA) hacia políticas orientadas al desarrollo sostenible de la región. Utilizando el método histórico-deductivo y la metodología de revisión sistemática de la literatura, a través del empleo de fuentes primarias y referencias bibliográficas especializadas en la temática, el supuesto analítico central es que la OTCA ha venido superando su inmovilismo institucional para consolidarse como pilar de la integración amazónica mediante el desarrollo sostenible, principalmente a partir de la firma de la Declaración de Belém durante la Cumbre Amazónica de 2023. En consecuencia, se busca reiterar que los beneficios de la integración son multiplicadores y difusores, teniendo como principales objetivos la reducción de las asimetrías regionales, la construcción de una identidad regional y la ampliación de la participación de componentes económicos y sociales.

Palabras clave: Amazonía; Organización del Tratado de Cooperación Amazónica; desarrollo sostenible; Declaración de Belém.

Résumé

Étant donné que le biome amazonien est, par nature, partagé, l'intégration de l'Amazonie sud-américaine constitue un préalable indispensable à son insertion dans l'économie mondiale, permettant d'éviter l'isolement et de stimuler la réflexion sur les impacts politico-économiques de la coopération, ainsi que sur les perspectives à long terme de ce processus dans un contexte mondialisé. En d'autres termes, il s'agit de ratifier la relance institutionnelle de l'Organisation du Traité de Coopération Amazonienne (OTCA) en vue de la construction d'une force de dissuasion destinée à défendre les zones stratégiques, sous la responsabilité exclusive des pays amazoniens. Cet article a pour objectif de présenter l'évolution historique de l'Organisation du Traité de Coopération Amazonienne (OTCA) vers des politiques orientées vers le développement durable de la région. En recourant à la méthode historico-déductive et à une méthodologie de revue systématique de la littérature, à partir de sources primaires et de références bibliographiques spécialisées dans le domaine, l'hypothèse analytique centrale est que l'OTCA est en train de sortir de son immobilisme institutionnel pour s'affirmer comme pilier de l'intégration amazonienne par le biais du développement durable, notamment depuis la signature de la Déclaration de Belém lors du Sommet de l'Amazonie en 2023. En conséquence, il s'agit de réaffirmer que les bénéfices de l'intégration sont multiplicateurs et diffus, avec pour principaux objectifs la réduction des asymétries régionales, la construction d'une identité régionale et l'élargissement de la participation des composantes économiques et sociales.

Mots-clés : Amazonie; Organisation du Traité de Coopération Amazonienne; développement durable; Déclaration de Belém.

1 INTRODUCTION

Historically, the Amazon has been viewed as one of the last frontiers of global capitalist expansion, perceived as a geopolitically strategic area given the global perspective of scarcity of natural resources necessary for the growth of the world economy. Consequently, the Amazon countries face numerous challenges: domestically, there is the issue of their occupation and integration, as well as the effective presence of the State; regionally, integration with neighboring countries under the historical maxim of integrating so as not to surrender, from a Pan-Amazonian perspective; internationally, the problem of the historical dispute over their territories with the dichotomy of sovereignty or internationalization.

Since the Amazon biome is shared by nature, the integration of the South American Amazon is an indispensable prerequisite for integration into the global economy, avoiding isolation and stimulating reflection on the political and economic impacts of cooperation, as well as the long-term prospects of this process in a globalized scenario. In other words, it ratifies the institutional resumption of the Amazon Cooperation Treaty Organization (ACTO) for the construction of a deterrent force aimed at defending strategic areas under the exclusive responsibility of the Amazon countries.

This article aims to present the historical evolution of the Amazon Cooperation Treaty Organization (ACTO) towards policies directed towards the sustainable development of the region. Using the historical-deductive method and the methodology of systematic literature review through the use of primary sources and specialized bibliographic references on the subject, the central analytical assumption is that ACTO has been emerging from its institutional immobility to establish itself as a pillar of Amazon integration through sustainable development, mainly since the signing of the Belém Declaration during the Amazon Summit in 2023. Consequently, it seeks to reiterate that the benefits of integration are multiplier and radiating, with the main objectives being the reduction of regional asymmetries, the construction of a regional identity, and the expansion of the participation of economic and social components.

This work is divided into three sections, in addition to this introduction and the final considerations. The first part will present a historical analysis of the creation of the Amazon Cooperation Treaty Organization (ACTO). Subsequently, the main cooperation and integration projects for the sustainable development of the region supported by

ACTO will be formalized. And, in the third and final section, the main characteristics of the Belém Declaration of 2023 will be presented, highlighting the document as a possible innovative milestone for sustainable Amazon development.

2 THE HISTORICAL CONTRIBUTION OF THE AMAZON COOPERATION TREATY (ACT) TO THE CELEBRATION OF NEW AGREEMENTS

To constitute a whole through the addition or combination of parts or elements in order to form an organized society, regional integration presents itself as a fundamental modality for countries that wish to elevate their status quo in the international system. According to Padula (2010, p. 44), the first systematized contributions of international relations theory to the theory of regional integration were made by Karl Deutsch and David Mitrany, marked by the "first wave" that began after the Second World War and which had the experience of European integration as its icon in the 1950s (Padula, 2010, p. 17-18).

Haas (1964, p. 710) states that integration means "the process of transferring exclusive expectations of benefits from the nation-State to some larger entity". For Herz and Hoffmann (2004, p. 168), "regional integration "can be defined as a process along which initially independent actors unify, that is, become part of a whole,"[1] whether governmental or non-governmental, national, subnational, or transnational. However, while in its initial phase integration visibly had a purely economic focus, with the result of countries' efforts aimed at development (Chiarella; Cortegiano Junior, 1995, p. 27), its multifaceted character must be highlighted, interested in promoting policies that favor both socioeconomic development and the reduction of inequalities and asymmetries (Santos; Diniz Júnior, 2017).

> Integration is a joint decision-making project aimed at overcoming political, economic, physical, and social challenges between neighboring (or non-neighboring) countries that collaborate in the management of common resources and assets; it is an instrument, a tool, a means to overcome underdevelopment and leverage a projection of regional power at the international level. In the South American case, it encompasses strengthening the region's international position in the world system, addressing inequality/deconstructing regional asymmetries, building a regional identity, self-determination among peoples/nations, and

[1] Free translation by the translator.

> expanding the participation of economic and social components (Rodrigues, 2022a, p. 127).[2]

Since its incorporation into the world system in the 16th century, South America has faced physical obstacles to its integration, "which has resulted, precisely, in a low degree of interdependence between national economies, still marked today by great economic extroversion"[3] (Almeida, 2006, p. 15). However, it is recognized that without South American integration, local economies could be exposed to global marginalization (Kelly, 1997, p. 159), which has intensified the "awareness that small isolated countries will not be able to cope with the growing problems posed by overcoming underdevelopment"[4] (Furtado, 1970, p. 290).

Consequently, it is of paramount importance to analyze to what extent regional integration can act as a catalyst for the common objectives of the Amazon countries. It is in this sense that the Amazon Cooperation Treaty (ACT) gains fundamental prominence for the integration of the Amazon region in the 21st century. Signed on July 3, 1978, in Brasília, by the eight countries belonging to the Amazon Basin, its objectives include raising the standard of living of their populations, the rational and ecological use of flora and fauna, scientific and technological research, and the exchange of information between the parties (Ribeiro, 2005, p. 258). For Mattos (2011, p. 117-118), its five fundamental principles are: exclusive jurisdiction of the Amazon countries in their development and protection; national sovereignty in the use and preservation of natural resources; regional cooperation; balance and harmony between development and ecological protection; and equality among all partners.

According to the author Calmon de Passos (2009), environmental problems are some of the factors that have contributed to altering the perspective of the international community, making them a global issue. It was with this new recognition that, in 1972, world authorities took the initiative to develop legal instruments aimed at protecting the international environment, supported by a new agenda planned by the United Nations Conference on the Human Environment, also called the Stockholm Conference (Calmon de Passos, 2009, p. 2).

[2] Free translation by the translator.
[3] Free translation by the translator.
[4] Free translation by the translator.

In that same year, the Stockholm Conference brought environmental concerns to the forefront, resulting in the development of international environmental protection measures that raised concerns among the leaders of the Amazon region. Furthermore, the Brazilian government's main reason for initiating the first regional agreements stemmed from a new international context disseminated by the Club of Rome and was largely influenced by the group's impact (Nunes, 2016, p. 223).

In addition to this, Nunes (2016) highlights some of the reasons for the signing of the Amazon Cooperation Treaty:

> [..]the desire to assert sovereignty over the territory and natural resources, in order to guarantee the continuity of economic projects in the region and ward off the specter of internationalization; the desire to present to the international community a document that safeguarded the exclusive management of Amazon problems in line with environmental protection; and, finally, Brazilian concern about possible isolation due to the construction of the Itaipu dam (Nunes, 2016, p.223).[5]

The main expectation of the actors involved in the creation of the Amazon Cooperation Treaty was to reiterate among the signatory states themselves the recognition of sovereignty over the part of the Amazon that belongs to them, as Zevallos (1993) states:

> The importance of the ACT lies in the recognition of the sovereignty of each of the signatory countries over its corresponding part of the Amazon – this is called regionalization – as a concept opposed to internationalization, also allowing discussion and the taking of positions on the problems of the whole[...][6]

In summary, it is clear that three main reasons motivated the ratification of the Amazon Cooperation Treaty: to categorically reaffirm the exclusive sovereignty of the Amazon countries over the region, rejecting the idea of internationalization; to seek the economic development of the Amazon territories through the rational exploitation of natural resources and international cooperation; and to resolve the imbroglio involving the Itaipu dam with Brazil and Argentina (Fernandes, 2013).

But, beyond the arguments presented so far, what are the reasons that led the Amazon states to decide to cooperate in resolving political issues related to the environment? This is the question that Le Prestre (2000) will ask and attempt to answer throughout his work. In the following passage, he argues that the transnational dimension

[5] Free translation by the translator.
[6] Free translation by the translator.

of the environment, in this case of the Amazon, is not limited to a single state: "the transnational character of numerous environmental issues obliges states to conclude agreements with other countries, on which the achievement of their national and international objectives depends"[7] (Le Prestre, 2000, p. 284).

The delay in crystallizing another regional agreement in the Amazon is due to the human and economic void in the region. Even so, Brazil forwarded the initiative to create the Amazon Cooperation Treaty (ACT) with the intention of serving as an instrument to guarantee the sovereignty of the Amazon countries over the northern portion of South America, as well as to promote the development of the region with the use of its natural resources, through cooperation between the Amazon countries themselves (Macedo, 2021, p.194).

Initially, the ACT is commonly remembered for its long period of inactivity from 1978 to 1989. Although the Treaty itself contributed to improving and enhancing relations between the Amazon countries (Silva, 2012, p. 106), the 1980s would be marked by several public debt crises, economic instability, and social redemocratization processes that profoundly affected the South American states.

Given this context, the efforts of these countries will be directed, at the regional level, towards areas other than the environmental one, as identified by Quiroga and Marcovitch (2003) and Silva (2012). Macedo (2008) reinforces the thesis that the Amazon nations had a greater interest in closer ties in the commercial area:

> It is with the Amazon Cooperation Treaty (ACT) structured in this way, therefore, that the future of this extremely important geographical area, where the largest continuous tropical forest in the world is located, with extraordinary biodiversity, begins to be considered jointly with the countries over which the Amazon extends. It cannot be denied, as Silveira (2005, p. 72) states, that since its creation in the 1970s until today, there has been a significant rapprochement between the Amazon nations, notably in the commercial and technical area, in which the economic interest of the parties involved has predominated (Macedo, 2008 p.188).[8]

The ACT facilitated closer ties between the countries of the region. This statement will be better understood with some of the international commitments made between Bolivia, Brazil, Colombia, Peru, Venezuela, and Ecuador, as pointed out by Silva (2012). Since 1989, the ACT member states have been making it more operational and efficient,

[7] Free translation by the translator.
[8] Free translation by the translator.

recognizing that the existing structure was not very well suited to the renewal of function that was intended to be implemented (Antiquera, 2006, p. 136). The first problem identified by the authors Filippi and Macedo (2022, pp. 194-195) refers to some of the dissatisfactions of the Amazon countries in relation to the ACT, highlighting institutional issues: the general guidelines did not specifically outline the duties of each member state nor the concrete policies for the region; it lacked mechanisms capable of resolving possible controversies; finally, the internal structure of the ACT had a simple layout, presented in its articles and preamble, without any internal division or subdivision.

In his thesis, Antiquera (2006) cites, in addition to the aforementioned institutional issues, three specific points that led to the institutional change creating the permanent secretariat. The first point is the history of little cooperation and centuries-old conflicts. For an international agreement to be cooperatively effective, historical differences and conflicts that may involve the interested members must be considered. This can bring new conceptions of the use of tools in response to the challenges of the Amazon territory. For example, the political harmony that would require greater alignment of conceptual and technological instruments, such as the collection of data from each country with different criteria and variables, will make it difficult to formulate proposals common to continental Amazonia (Antiquera, 2006, pp. 136-137). In addition to this difference in conceptions, there will also be the difficulty of overcoming various historical border disputes between the Amazon countries.

The second point highlighted by Antiquera (2006, p. 140) is the lack of knowledge about the region. It is frequently described as a mythical area in a generalizing way, without sufficient understanding of its particularities, specificities, and inhabitants. This lack of knowledge hinders the formulation of effective public policies, and the combination of this challenge with the precarious infrastructure of the region further complicates the development of active projects and the acquisition of international resources.

The third point is the lack of resources, a fundamental theme for understanding the absence of results from the ACT. In the 1980s, Latin American countries faced an economic crisis that would worsen any ongoing public policy project due to budgetary constraints. This crisis occurred shortly after the Amazon Cooperation Treaty came into effect. That said, Antiquera (2006) highlights two problems related to the lack of

resources: the first is the economic insufficiency of the countries to finance their projects, including the ACT; and the second is the constant need to seek external sources of funding. Therefore, the financial involvement of Amazon countries, depending on external support, would limit the choices of beneficiaries. But for this to be viable, it was necessary to have an organized structure capable of formulating and attracting projects that met the requirements of international funders. Therefore, the author outlines that the initial idea of excluding countries outside the region is set aside in favor of attracting new partners who can financially support their plans (Antiquera, 2006, pp. 140-142).

Over the years, environmental issues intensified even further around the challenges faced in the Amazon region, adding to this factor the unsatisfactory institutional perception of the ACT to strengthen the foundations for Amazonian cooperation to reach another level, through an International Organization (Simões, 2012, p. 39). According to Teixeira (2006, p. 10):

> [...]the beginning of the 1990s would reverberate with strong pressures on Brazil, especially the Amazon, which would become a target of globalist discourse, notably due to the scenario of forest destruction, the death of Chico Mendes, and the violation of indigenous rights, which led to a shift in Brazilian policy towards the region.[9]

In other words, the 1990s brought to light new notions of environmental issues. The Rio-92 Conference and the Brundtland Report introduced the idea of sustainability at an international level, although a more critical look leads to ambiguous interpretations of the latter (Santos, 2000). Due to this new vision of the use of environmental goods, the Amazon Cooperation Treaty would undergo institutional changes (Macedo, 2020, p. 180).

Following several meetings to revise the Amazon Cooperation Treaty's structure, significant changes began after the third Meeting of Ministers of Foreign Affairs in Quito in 1989, repositioning the treaty as a tool for Amazonian sub-regional integration (Filippi; Macedo, 2022, p.). The Amazon Cooperation Treaty Organization (ACTO) was created to stimulate cooperation among the Amazon countries, thus resulting in projects and initiatives for international cooperation in the region. It itself will be responsible for promoting political coordination among the signatory members and for reaffirming their

[9] Free translation by the translator.

sovereignty in the use and conservation, through the sustainable development of their Amazon territories (Silva, 2012, p. 130).

In 1995, the bloc's foreign ministers decided to establish a Permanent Secretariat (PS), based in Brasília, to host the Pact, and the new status of recognition of international legal personality would allow its future administrative department, on a permanent basis, to sign agreements with international organizations, participate in multilateral forums, and obtain international loans to promote environmental preservation and infrastructure projects important for the integration of the region (Santos, 2000, p. 114).

In fact, the Amazon Cooperation Treaty Organization only became operational in 2002, when Colombia, the last party to the ACT, ratified the Amendment Protocol, which altered the wording of Article XXII of the original ACT, changing the temporary secretariat to a permanent one. From December 13, 2002, the Permanent Secretariat would exercise its duties, which allowed it to be: a consensus builder; a facilitator of political and technical dialogues; a coordinator; a manager of support for regional and international cooperation; a manager of regional information; and a promoter of actions aimed at strengthening the internal institutional capacity of member countries (Santos, 2000, p. 115).

The transformation of the ACT into an international organization with legal personality allows for a reduction in uncertainties and the construction of a more regionally articulated political environment. Taking the 1989 Amazon Declaration as an example, the pact sought to represent an effort of cohesion and awareness among the countries of the Amazon region regarding the need to intensify the effective implementation of a regional integration and cooperation body that would enable the maintenance of sovereignty and the promotion of development, allowing the Pan-Amazon region to "awaken from its centuries-long slumber"[10] (Mattos, 2011, pp. 132-133). Furthermore, from a regional perspective, the ACTO will be constituted as a bridge for the project of articulation among South American countries (Antiquera, 2006, pp. 166-167).

The Amazon Cooperation Treaty establishes two institutional bodies understood as branches of the Amazon cooperation process: the Amazon Cooperation Council

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(CCA); and the Permanent National Commissions. As pointed out by Silva (2012, p. 132), the CCA's responsibilities include conducting intergovernmental policy, as well as directing the fulfillment of projects and decisions within the scope of the ACT. Article XXI of the ACT addresses the functions of the Amazon Cooperation Council, among them:

> (...) to take under consideration initiatives and plans presented by the Parties as well as to adopt decisions for undertaking bilateral and multilateral studies and plans, the execution of which, as the case may be, shall be the duty of the Permanent National Commissions; to evaluate the implementation of bilateral or multilateral interest; to draw up the Rules and Regulations for its proper functioning (ACT, 1979, Article XXI).[11]

In the Permanent National Committees, the following will be assigned:

> the application of the Treaty's provisions in their respective territories; the execution of decisions and agreements adopted at the Meetings of Ministers and the Amazon Cooperation Council; proposing measures and actions of internal and external policy related to the topic; ensuring the proper implementation of the Treaty's plans, programs and projects (Silva, 2012, p.133).[12]

That is, these are bodies that operate within the national scope of the ACT members and, according to the decisions of the Meetings of Ministers and the Amazon Cooperation Council, coordinate joint actions with the Special Commissions (Silva, 2012, p. 133). Antiquera (2006, p. 76) points out that, from a meticulous reading of the Amazon Cooperation Treaty, the agreement reveals great caution regarding sovereignty, in which it is perceived that interests within the national scope are considered a priority, while multilateral cooperation is relegated to a secondary level. Following this reasoning of the author, one can perceive the idea of priority in a national plan of each State, in the preamble of the ACT itself, which states that both “socioeconomic development and the preservation of the environment are responsibilities inherent to the sovereignty of each State and that cooperation between the Contracting Parties will serve to facilitate the fulfillment of these responsibilities [...]” (TCA, 1978).

However, after more than 40 years of the Amazon Pact's implementation, few concrete advances have been made: "in any circumstance, it is necessary to emphasize that the Amazon Pact has not yet had sufficient deterrent power, in the face of rich

[11] Taken from the original at: https://treaties.un.org/doc/Publication/UNTS/Volume%201202/volume-1202-I-19194-English.pdf.
[12] Free translation by the translator.

countries, regarding their ambitions in relation to the Amazon" (Ribeiro, 2005, p. 259). Given that the integration of the South American Amazon is revealed as one of the main objectives of the institutional arrangements, it is necessary to resume and intensify the initial political-institutional spirit of the Treaty's signing, recognizing the indispensability of joint action, since integration is one of the best antidotes to promote cooperative sustainable development projects.

Therefore, even though the ACT prioritized a national perspective and conceived of multilateral action as subsidiary and complementary to national actions, the change from a temporary to a permanent secretariat will alter this idea, including with regard to sustainable development. This new phase of the Organization is of fundamental importance for understanding its role as a catalyst for the sustainable development of Amazon countries in the 21st century.

3 ACTO AND COOPERATION AND INTEGRATION PROJECTS FOR THE SUSTAINABLE DEVELOPMENT OF THE REGION

The environmental movement, which emerged from the Club of Rome after the publication of the Meadows Report in the early 1970s, transcended the scientific environmental issue and entered the economic domain. That is, in general, it established the emergence of environmental preservation as a topic of economic, social, and political relevance. This movement pointed to a possible, if not probable, incompatibility between economic growth and the preservation of environmental resources, based on the experiences of the 20th century. As in 1972, at the Stockholm Conference, the thesis of Ecodevelopment gained prominence, according to which economic development and environmental preservation are interconnected and depend on each other to achieve the dimensions of sustainable development (Freire *et al.,* 2006, pp. 13-14).

The concept of sustainable development is dynamic and always open to many interpretations, which reflect perspectives considered culturally appropriate and of local relevance (UNESCO, 2005, p. 26). However, the concept gained strength with the publication, in 1987, of the book Our Common Future, by the Commission on Environment and Development, which defined it as: "sustainable development is development that meets the needs of the present without compromising the ability of

future generations to meet their own needs"[13] (World Commission on Environment and Development, 1991).

The idea of sustainability in environmental policy emerged as an attempt to reconcile the demands of economic growth with the demands for forest preservation (Silva, 2012, p. 110). This new concept only gained global reach and, at the same time, became incorporated into the discourses of world politics with the Brundtland Report in 1987 (Ipiranga, 2011). Furthermore, some changes were even more evident during the United Nations Conference on Environment and Development, also known as Rio-92, in 1992, with the objectives of Agenda 21; and at the Johannesburg Conference in 2002, with the broadening of the traditional vision of sustainability to include the fight against poverty and social justice.

Since the themes of sustainable development have become essential in international relations, this demand led the Presidents of the Amazon countries to incorporate this new language into the Amazon Declaration (Silva, 2012, p. 110). This process took place through debates with the participation of the eight member countries of the ACT during the Tarapoto Process. As expressed by Silva (2012), the Tarapoto proposal would create “common tools for planning sustainable development, through instruments for quantitative and qualitative analysis of sustainability, established through consultation and validation processes at national and regional levels”[14] (Silva, 2012, p. 111).

The Amazon plays a strategic role in sustainable development and requires interdependence and complementarity for the strategies undertaken in the Amazon regions of the ACT countries (Helissa, 2003, p. 12). Additionally, it is within the context of this debate that a new phase in the process of regional cooperation and integration among Amazon countries began after the establishment of the Permanent Secretariat (PS). Initially, the 2004-2012 Strategic Plan would be crucial for the dynamics of increasing cooperation between Member States and other international organizations, as well as for addressing new environmental challenges.

The Strategic Plan was approved in 2004 at the VIII Meeting of Ministers of Foreign Affairs of the Amazon States, with the aim of guiding the PS/ACTO in four

[13] Taken from the original at: https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf.
[14] Free translation by the translator.

strategic axes and six cross-cutting programmatic areas (OTCA, 2004, p. 21). That is, this Strategic Plan would be a political guideline that attempted to respond to the new challenges that the Amazon demanded of ACTO. The Plan establishes that ACTO's decisions and administration must be aligned with various mechanisms that aim to "order" and give "coherence" to the organization's present and future programs and projects, enabling the determination of the cross-cutting impacts of the initiatives carried out and, thus, the corresponding strategic objectives.

The four strategic axes presented by the 2004-2012 Strategic Plan were structured as follows: Conservation and Sustainable Use of Renewable Natural Resources; Knowledge Management and Technological Transfer; Regional Integration and Competitiveness; and Institutional Strengthening (OTCA, 2004, p. 24). Given that the focus of this work is sustainable development, attention will be concentrated on the first axis, which addresses the Conservation and Sustainable Use of Renewable Natural Resources, and on the third axis, Regional Integration and Competitiveness, with one of its dimensions of regional integration.

Within the framework of Conservation and Sustainable Use of Renewable Natural Resources, as stated in the Strategic Plan, the main challenge for the ACTO Member States is "to towards creating economic opportunities for the Amazon populations and the nations as a whole."[15] Furthermore, " it is important to explore and develop sustainable uses of biodiversity and of natural resources of the Amazon region, as a viable mean to stimulate mechanisms that create networks that promote Amazon products within a sustainable framework."[16] (OTCA, 2004, p. 25). Also, according to the Plan, this new approach to managing environmental resources could encourage new economic activities for the "generation and retention of income" in other sectors, such as genetic knowledge, ecotourism, timber and non-timber derivative products with the International Tropical Timber Organization (ITTO) certificate, phytotherapeutics, cosmetic and food products (OTCA, 2004, p. 25).

One of the priorities of the Member States, as stated in the Strategic Plan, is to establish the foundations for sustainable development, generating social well-being and

[15] Taken from the original at: https://otca.org/wp-content/uploads/2021/01/Strategic-Plan-2004-2012.pdf (p. 25).
[16] Taken from the original at: https://otca.org/wp-content/uploads/2021/01/Strategic-Plan-2004-2012.pdf (p. 25).

increasing the countries' participation in the global economy in the long term. The Strategic Plan will add, in its third axis, three series of dimensions of regional integration that aim to focus their efforts among the members. The first issue addresses Amazonian water resources as a pillar of development, focusing on sustainable management from a regional perspective and with integrated action among the countries of the Amazon basin. The second point reinforces the need for Amazon countries to coordinate and converge on economic policies and the development of precise actions for regional sustainable development, which is a challenge for integration into international markets. Finally, the third point highlights the challenges in building cooperative instruments amidst national inequalities and asymmetries between countries. Therefore, the ACTO must align with the Millennium Development Goals for 2015 (and currently with the UN Sustainable Development Goals (SDGs) for 2030), aiming for sustainable development. The Plan also recognizes the importance of strengthening communication and cooperation as a way to integrate common elements among the countries of the region (OTCA, 2004, pp. 33-34).

According to Simões (2012), from 2009 to 2014, after the creation of the PS, a new phase of revitalization of the ACTO began with the launch of the Strategic Agenda 2010-2020, which originated the Manaus Declaration. For him, it is in this context that "the ACTO will gain a renewed and modern role as a forum for cooperation", soon after, "recognizing the sustainable development of the Amazon as a priority, through an integral, participatory, shared and equitable administration, as a way to give an autonomous and sovereign response to current environmental challenges"[17] (Simões, 2012, pp. 40-41).

The Strategic Agenda was approved in November 2010 at the 10th Meeting of Ministers of Foreign Affairs of the ACT, which included the vision, mission, and strategic objectives of the ACTO. Regarding the Amazon Region, the ACTO aims to achieve sustainable development through the balanced use, protection, and conservation of its resources. Furthermore, it aims to be an organization recognized in its member countries and internationally as a benchmark in regional cooperation.

Its mission is to be a permanent forum for cooperation, exchange, and knowledge, with principles of reducing regional inequalities among Members and assisting in national socioeconomic progress. Finally, the strategic objectives are: to ensure respect for and

[17] Free translation by the translator.

promotion of the interests and sovereignty of Member Countries; to facilitate exchange and cooperation among Member Countries, promoting sustainable development and sustainable ways of life of a strategic nature in the region; and to promote the coordination of Member Countries' Plans and Programs for the development of Amazonian populations (OTCA, 2010, pp. 15-16).

According to Rodrigues (2022b), the Strategic Cooperation Agenda is one of the pillars for the new sustainable development agenda of the ACTO:

> The Amazonian Strategic Cooperation Agenda encompasses a series of cooperation initiatives in the area of conservation and sustainable use of renewable resources. Its main objective is to enable dialogue to analyze the impacts of incorporating the Amazonian regions into national economic systems through road and river networks and information technologies, in harmony with the preservation of ecosystems. Furthermore, supported by the United Nations Framework Convention on Climate Change, the Paris Agreement, and the 2030 Agenda for Sustainable Development, its actions are oriented towards consolidating the ACTO as a key actor in strategic issues for the region (Rodrigues, 2022b, p. 190).[18]

Additionally, the two cross-cutting approaches for implementing the Strategic Agenda are presented: conservation and sustainable use of renewable natural resources; and sustainable and social development (ACTO, 2010, p. 17). Furthermore, the Strategic Agenda presents several approaches to various themes divided into sub-themes, including: forests, water resources, management, monitoring and control of wild flora and fauna species threatened by trade, protected areas, sustainable use of biodiversity and promotion of "bio-trade", research, technology and innovation in Amazonian biodiversity, protection of the traditional knowledge of indigenous peoples and other tribal communities, environmental health, technology to improve the efficiency and effectiveness of health interventions, financing of the health agenda, strengthening the tourist image of the Amazon, as well as emerging themes such as climate change, regional development and energy (OTCA, 2010, p. 19).

According to Silva's explorations (2012, p. 160), the Strategic Cooperation Agenda gave greater attention to forest issues, establishing a broad set of short-term activities. For Rodrigues (2022b), two other projects also stand out as milestones in this

[18] Free translation by the translator.

green shift of the ACTO in the first decades of the 21st century: the ACTO/UNEP/GEF Project (2012) and the Bioamazon Project (2016).

However, as seen throughout its implementation and institutional maturation process, some setbacks to the environmental agenda within the ACTO were observed in the 2010s, mainly concerning the largest Amazonian country. During Jair Bolsonaro's Brazilian government, actions aimed at making implemented environmental policies more flexible were seen, and the president himself made statements contrary to the environmental preservation agenda (Martoni, 2019), causing delays to the environmental governance system in the last decade.

A practical example was the implementation during the Bolsonaro government of the "repeal" measures, which annulled decrees related to environmental areas because they were considered "unnecessary." The National Environment Council (CONAMA), the Chico Mendes Institute for Biodiversity Conservation (ICMBio), and the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA) were politicized and had their budgets reduced (Rodrigues, 2022b; Loureiro, 2023), with their composition altered, weakened, and excluded, as well as the displacement of the participation of the scientific community. Conservation Units were removed from the climate change sectors; the Amazon Fund was paralyzed; and, lastly, the encouragement of deforestation, fires, illegal logging, and land grabbing was a constant variable in the Bolsonaro government (Seixas *et al.*, 2020, p. 18).

Although the Bolsonaro government positively established the Leticia Pact on September 9, 2019, with the objectives of combating deforestation, creating forest restoration initiatives, sustainable use of natural resources, actions to strengthen indigenous peoples, and the creation of educational campaigns on the importance of the region (as well as the exchange of information in real time and monitoring in the face of attempts to internationalize the Amazon), it is easily noticeable that the Amazonian ecosystem has been at high risk for many years (and intensified under this administration), as already highlighted by Becker (2015, p. 79) "due to the national/transnational model adopted, and because transnational corporations have long participated in the environmental and social degradation of the Amazon."[19]

[19] Free translation by the translator.

Therefore, it is important to point out that several initiatives are running counter to this Bolsonaro project. One of the most interesting in terms of research is the "Amazon 2030" project, an initiative by Brazilian researchers to develop a sustainable development plan for the Brazilian Amazon, with the aim of enabling the region to achieve a higher level of economic and human development, and to achieve the sustainable use of natural resources by 2030 (Amazon 2030, 2025).

In monitoring the Amazon, the Amazon Mission project, from the National Institute for Space Research (INPE), will provide remote sensing data to observe and monitor deforestation, especially in the Amazon region, seeking to act in synergy with existing environmental programs, mainly through the planned use of three remote sensing satellites (Amazonia 1, Amazonia-1B and Amazonia-2) (INPE, 2024).

Within the framework of paradiplomacy, the Interstate Consortium for Sustainable Development of the Legal Amazon (2021) launched, in July 2021, the Green Recovery Plan. This consists of a transition strategy towards a green economy for the Amazon region that is compatible with combating inequalities, generating employment and income, and achieving sustainable economic growth. Its four pillars include curbing illegal deforestation, a green economy with sustainable production, green technology/capacity building, and green infrastructure (Alvares; Rodrigues; Narita, 2022).

Within the context of the South American Amazon, linked to the debate on climate security, regional efforts have also become increasingly prominent since the 2020s. In this sense, intergovernmental coordination has found one of its main pillars in the Belém Declaration project, as will be analyzed below.

4 BELÉM DECLARATION: A MILESTONE FOR PAN-AMAZONIAN SUSTAINABLE DEVELOPMENT

As previously highlighted, one of the key milestones for a sustainable development project in the Amazon countries was the creation of the Belém Declaration at the Amazon Summit, held between August 8 and 9, 2023. At this meeting, the leaders of the States Parties to the ACTO brought to the forefront the main international demands related to the environment, focusing on the Amazon region. They decided to coordinate efforts among their governments, promoting a new agenda that included 113 cross-cutting

objectives and principles for its implementation. Among these, the following can be highlighted:

> under the objective of sustainable development, conservation of forests, sustainable use of biodiversity, forests and water resources, urgent action to avoid the point of no return in the Amazon, the fight against deforestation and illicit activities in the region, economic development with social inclusion and generation of income and employment, based on mechanisms of social participation, particularly of indigenous peoples and local and traditional 8 communities, and the strengthening of ACTO.[20] (OTCA, 2023a, p.8).

This Declaration will play a very important role, as it outlines, in its main objectives, the implementation of a cooperation agenda in the Amazon, guided by sustainable development and a commitment to an integrated vision and collective action. As mentioned earlier, the Declaration reaffirms its commitment to social aspects, promoting active participation and respect for the rights of traditional peoples. Furthermore, it also highlights economic aspects that seek the inclusion of the region, with the aim of preventing the Amazon from reaching a point of no return. (OTCA, 2023a, p.1).

Throughout the Declaration, some of the cross-cutting objectives and principles reflect the commitment of the leaders of the States Parties to the pursuit of sustainable development, with the ACTO being:

> the sole intergovernmental coordination body for the eight Amazon countries with regard to jointly implementing projects, and actions that produce equitable and beneficial results to Amazon countries, due to its institutionality, its extensive knowledge of the region, and the 7 relevant experience of its Permanent Secretariat in coordinating dialogue and implementing development cooperation initiatives[21] (OTCA, 2023a, p.7).

It is also added that the ACTO's medium- and long-term objectives are in line with the 2030 Agenda and its Sustainable Development Goals (SDGs) (OTCA, 2023a, p. 15). For example, the document will include the importance of eradicating hunger, poverty, and violence against Amazonian populations, an indispensable requirement for the sustainable development of the region. To this end, the document condemns the

[20] Taken from the original at: https://otca.org/wp-content/uploads/2023/10/Declaration-of-Belem.pdf (pp. 7-8).
[21] Taken from the original at: https://otca.org/wp-content/uploads/2023/10/Declaration-of-Belem.pdf (pp. 6-7).

proliferation of unilateral trade measures that, based on environmental standards, result in trade barriers, since these measures will harm small producers in developing countries in their efforts to promote Amazonian products and eradicate poverty, including hunger. (OTCA, 2023a, p.5).

In the Declaration itself, the topic "Sustainable Infrastructure" listed three measures aimed at strengthening public policies, namely: 68. cooperation and dialogue for sustainability standards in the execution of infrastructure projects in the Amazon; 69. promotion of technological inclusion, eliminating digital divides and empowering communities, supporting environmental monitoring and regulating joint infrastructure mapping; and 70. deepening the integration of clean energy to promote access to energy in isolated locations in the Amazon countries.[22] (OTCA, 2023a, p.29-30).

Specifically, in the section on "Amazon Cities" in the Belém Declaration, the commitment within the ACTO to establish the Amazon Cities Forum will be highlighted, aiming to strengthen collaboration among local authorities of member countries. This forum will aim at the implementation, at the local level, of the 2030 Agenda and its Sustainable Development Goals. It will also seek to strengthen indigenous, local, and traditional leadership, promoting interculturality. In this context, three main proposals for action addressing the urban challenges of the Amazon will be identified, such as access to public services for Amazonian populations, and the development and implementation of public policies (OTCA, 2023a, p. 12).

Finally, in the section "Economics for Sustainable Development," thirteen measures are outlined to promote sustainable development in the Amazon region, highlighting:

(...)

71. promotion of the sustainable use of natural resources, family farming, forestry, and other areas, through integrated forest management, recognizing traditional agricultural production practices, which will include the recovery of degraded areas;

72. encouragement of geochemical studies on soils and hydrographic resources of the Amazon region to develop agroecological zoning and climate risk instruments, aiming to define suitable areas for productive activities, through sustainable means;

[22] Free translation by the translator.

73. development of a strategic agenda, executed by ACTO, for the integral development of production based on the sustainable use of Amazonian biodiversity resources;

74. establishment, within the scope of this strategic agenda, of a program of sustainable use production chains, with interests directed towards indigenous peoples and traditional local communities, aiming at forest management and recovery, income generation and promotion of quality of life, training and strengthening of productive organization, and sharing technologies for greater value aggregation for these peoples;

80. promoting the development of sustainable tourism, which will include typologies and morphologies specific to the region, such as nature tourism, cultural tourism, indigenous tourism, regenerative tourism, community tourism, and agro-ecotourism, to contribute to the sustainable development of the region; and,

81. adopting urgent measures to eliminate air, soil, and water pollution from the Amazonian rivers, in which countries commit to adopting public policies for sustainable production and strengthening waste management, the recyclability of materials, and the sustainability of economic chains for product recycling.

As pointed out in the official document "Amazonian Cooperation: Institutional Strengthening and Integrated Action" (2023), the Amazon Summit renews the political will regarding the region and strengthens it as a provider of solutions and opportunities, aiming to sustain the leading role of the ACTO among the main actors in the regional and global scenario for sustainable development.

> With new and broader guidelines and a pragmatic approach, the Belém Declaration propels the work of the ACTO, which, in turn, implies strengthening national, binational, and trinational action among Member Countries, including more actions in border areas. Furthermore, the Declaration reinforces, strengthens, and modernizes the institutional framework and governance of the ACTO by updating the organization's mandates and encouraging the use of new management and consolidation tools[23] (OTCA, 2023b, p. 14).

In other words, the Belém Declaration ratifies that the preservation of ecological balance is not inversely proportional to the exploitation of regional potential, since it is possible to achieve a new pattern of economic development that overcomes the dilemma of conservation versus use with destruction. In other words, "only by assigning economic

[23] Free translation by the translator.

value to the forest will it be able to compete with commodities, imposing the need for a true scientific and technological revolution for this purpose."[24] (Becker, 2015, pp. 46-47).

Additionally, Rebelo (2024) confirms that the defense of the Amazon must be understood as a challenge for national policy. That is, when reflecting on strategic planning for the region, it is fundamental to understand its strategic value, assess its potential, and identify opportunities for utilizing Amazonian assets as crucial points for changing economic development. In other words, the South American Amazon has always been on the radar of two development projects: the first, aiming to make it untouchable and conserved, thus hindering its potential; and the second, seeking to make its resources accessible in a predatory and irrational way driven by pure economic short-sightedness. Therefore, instead of relying on an autonomous project, a third path of rational exploitation is envisioned, based on the promotion of Science, Technology, and Innovation (Nobre, 2019). This is a new production paradigm, capable of utilizing natural resources without destroying them.

In this respect, the initial outline of the Belém Declaration confirms the essential need to delineate strategies that mitigate negative environmental externalities as much as possible, since even the slightest possibility of destruction of the Amazon would mean the failure of any possibility of a political-strategic project oriented towards a Green Power Brazil (Rodrigues; Góes, 2024). Conversely, the resumption of the dream of a South American and Amazonian union could be represented by a new development model that preserves the great humid tropical forest, a Modern Biodiversity Economy (Rodrigues, 2022b).

5 FINAL CONSIDERATIONS

This article aimed to provide a historical and current overview of the Amazon Cooperation Treaty Organization's participation in sustainable development projects for the region. It noted that, although the ACTO has gone through turbulent periods and periods of low institutionalization, it is the only integration and cooperation project for the promotion of sustainable development policies in the region. Similarly, although still

[24] Free translation by the translator.

in its early stages, the project proposed by the Belém Declaration presents a high potential for positive socio-environmental externalities for the Amazon in the medium to long term.

It is worth highlighting that both the 5th Summit of Presidents of the Amazon Cooperation Treaty Organization (ACTO) (to be held between August 18 and 22, 2025) and the 30th United Nations Conference on Climate Change (COP30) (to be held between November 10 and 21, 2025) are two extremely significant events for consolidating the sustainable path initiated with the Belém Declaration (2023). Both seek to renew commitments to the Amazonian agenda and strengthen regional cooperation, ensure the well-being of its peoples, and project its voice on the global agenda. Consequently, their monitoring and analysis are fundamental for future research.

In conclusion, this work reiterates that regional integration is not purely political, nor purely economic-commercial, nor purely physical; it is a combination of distinct perspectives that complement and overlap each other, aggregating geopolitical, institutional, regulatory, and social demands that are dynamic and therefore transform over time. Even considering possible barriers in the Amazonian context – such as the lack of political convergence, the disparity in development and technological power, economic uncertainties, legal insecurities, and aversion to the loss of national sovereignty – the benefits of integration are multiplied and radiating, with the main objectives being the reduction of regional asymmetries, the construction of a regional identity, and the expansion of the participation of economic and social components.

The Amazon is one of the main pillars of the green transition project in the 21st century. For such a plan to succeed, it is necessary to articulate a Sustainable Political Economy Project with a Regional Sustainable Development Project, establishing a development path based on Science, Technology and Innovation, understanding its metabolic complexity and using its natural heritage without destroying it. Therefore, it is necessary to raise awareness among public agents and the population about the ecological problems involved, to promote the sustainable use of strategic natural resources, to intensify technical and scientific support made possible by the growth of researchers in and from the Amazon, and, fundamentally, to understand that regional integration is an inexorable path to sustainable development in a forest that knows no borders.

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Blue Amazon, a Brazilian perspective in the South Atlantic geopolitics

Amazônia Azul, uma perspectiva brasileira no contexto da geopolítica do Atlântico Sul

Amazonia Azul, una perspectiva brasileña en el contexto de la geopolítica del Atlántico Sur

Amazonie Bleue : une perspective brésilienne dans le contexte de la géopolitique de l'Atlantique Sud

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Abstract
The Blue Amazon is an area of great national and international interest, as it is a source of economic and natural wealth. Therefore, from a geopolitical perspective, security and defense initiatives in this area are essential. This text aims to discuss how actions among actors, civilians and military are coordinated to promote sovereign rights and sustainable development of the Blue Amazon, thus looking at its impacts on the economic, social and environmental axes. In the context of growing interest in the region, Brazil has made efforts not only to maintain peace and security, but also to preserve the environment. Thus, this paper seeks to briefly present the wealth and interests at stake, some of the Brazilian initiatives and cooperation with other countries, and key issues for the geopolitics of the South Atlantic that should be considered in Brazil's strategy of action, such as ZOPACAS.

Keywords: South Atlantic, Blue Amazon, geopolitics, Brazil.

Resumo
A Amazônia Azul é zona de grande interesse nacional e internacional, sendo fonte de riquezas econômicas e naturais. Logo, sob uma perspectiva geopolítica, mostram-se necessárias iniciativas de segurança e defesa nessa área. Este texto se propõe a discutir como são as ações

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coordenadas de atores civis e militares para a garantia da soberania nacional e do desenvolvimento sustentável da Amazônia Azul, e quais são seus impactos nas vertentes econômica, social e ambiental. No quadro do crescente interesse pela região, o Brasil tem envidado esforços para a manutenção da paz e da segurança, e também para a conservação do meio ambiente. Assim, pretende-se expor de modo sucinto a existência dessas riquezas e interesses, algumas das iniciativas brasileiras e de cooperação com outros países, além de questões importantes para a geopolítica do Atlântico Sul que devem ser consideradas na estratégia de atuação do Brasil, como no caso da ZOPACAS.

Palavras-chave: Atlântico Sul, Amazônia Azul, geopolítica, Brasil.

Resumen

La Amazonia Azul es una zona de gran interés nacional e internacional, ya que constituye una fuente de riquezas económicas y naturales. Por lo tanto, desde una perspectiva geopolítica, se hacen necesarias iniciativas de seguridad y defensa en dicha área. Este artículo tiene como objetivo analizar cómo las acciones coordinadas entre actores civiles y militares contribuyen a garantizar la soberanía nacional y el desarrollo sostenible de la Amazonia Azul, así como sus impactos en las dimensiones económica, social y ambiental. En un contexto de creciente interés por la región, Brasil ha realizado esfuerzos para mantener la paz y la seguridad, así como para conservar el medio ambiente. De este modo, se pretende presentar de forma concisa las riquezas e intereses involucrados, algunas iniciativas brasileñas y de cooperación con otros países, así como cuestiones clave para la geopolítica del Atlántico Sur que deben ser consideradas en la estrategia brasileña de actuación, como el caso de ZOPACAS.

Palabras clave: Atlántico Sur, Amazonia Azul, geopolítica, Brasil.

Résumé

L'Amazonie Bleue est une zone d'intérêt national et international majeur, constituant une source de richesses économiques et naturelles. Ainsi, dans une perspective géopolitique, des initiatives en matière de sécurité et de défense s'avèrent nécessaires dans cette région. Cet article vise à analyser comment les actions coordonnées d'acteurs civils et militaires contribuent à garantir la souveraineté nationale et le développement durable de l'Amazonie Bleue, ainsi que leurs impacts dans les dimensions économique, sociale et environnementale. Dans un contexte d'intérêt croissant pour la région, le Brésil a déployé des efforts pour maintenir la paix et la sécurité, ainsi que pour préserver l'environnement. L'objectif est donc de présenter de manière succincte ces richesses et intérêts, certaines initiatives brésiliennes et coopérations internationales, ainsi que des enjeux géopolitiques importants de l'Atlantique Sud à prendre en compte dans la stratégie brésilienne, comme le cas de la ZOPACAS.

Mots-clés : Atlantique Sud, Amazonie Bleue, géopolitique, Brésil.

1 INTRODUCTION

Thinking about the Amazon in all its richness and complexity allow us to associate the land and the marine, the green and the blue Amazons, since what happens in one, certainly has effects on the other. Therefore, defending sovereignty and promoting the sustainability of our "great Amazon" requires a comprehensive analysis of all challenges and opportunities. Consequently, the Amazon can be considered the heartland of the Anthropocene (Barros-Platiau *et al.*, 2025), the geological era marked by scientific warnings fueled by global risks stemming from the unsustainability of unequal growth on a global scale. However, when considering the Amazon, the terrestrial part – borders, forest, people, economic activities, among others – prevails over the maritime part (Guldberg *et al.*, 2025), and, generally, highlighting the need for a sustainable development model, necessary to replace "predatory patterns" in the region (Medeiros Filho *et al.*, 2025), or even the more recent socio-environmental approach presented in Inoue *et al.* (2025).

Along those lines, the text prioritizes a geopolitical approach, using the conceptual and analytical framework of the 21st century (Monteiro, 2021; Gonzales, 2024). Additionally, it adopts a political geography approach anchored in Castro's (2024, p. 78) proposal of the tripod: actor, space, and power. With the Brazilian State being the main actor, but not the only one (Gonzales, 2024, p. 77; Barros-Platiau *et al.*, 2024); the Blue Amazon as the space of action; and the challenges for the defense of national sovereignty over the space and its resources as a source of potential conflicts of interest.

The Blue Amazon (Carvalho, 2004, *apud* Barros *et al.*, 2015, p. 205) is part of the South Atlantic, the ocean which washes the Brazilian coast, as well as that of 23 other American and African countries. It is an environment full of natural riches and diverse ecosystems, but it is also the birthplace of complex economic, political, and environmental issues. The Brazilian maritime space has been called the Blue Amazon due to its size, which resembles that of the Brazilian Legal Amazon, which, according to the Brazilian Institute of Geography and Statistics (IBGE), in 2022, had approximately 5,015,146 km2. In April 2025, the United Nations Commission on the Limits of the Continental Shelf (CLCS) approved Brazil's request regarding the equatorial margin, adding approximately 360,000 km2 to Brazilian maritime space, according to Agência Gov (2025). The total area of the claim before the aforementioned Commission will result in a maritime area of approximately 5.7 million km2, according to the

Brazilian Navy (MB). As a result of the Continental Shelf Survey program conducted by the Brazilian Navy (phase 1 and phase 2), Brazil has requested primarily four areas, according to the Brazilian Navy website: in 2003, 960,000 km2, distributed along the entire Brazilian coast; and, subsequently to Continental Shelf Survey (LEPLAC) 2, 3 areas (South - 170,000 km2, in 2015; Equatorial Margin - 360,000 km2, in 2017; and Eastern/Southern Margin - 1.5 km^2, 2018).

However, the blue and green Amazon regions are similar not only in size, but also in the rich biodiversity found in these areas. The green biome is considered one of the largest and most diverse biomes in terms of fauna and flora (Veríssimo *et al.*, 2024; ISPN, 2025), while the blue biome contains its own ecosystems that provide services that make life on planet Earth viable (Seixas *et al*., 2023).

The maritime area is also where more than 80% of international trade passes through (in the Brazilian case, this figure reaches over 95%, according to the Brazilian Navy), and submarine cables are fundamental for global communication. The issue of sovereignty, which necessarily permeates this space, cannot be ignored. Coastal countries often have territorial disputes over sovereignty and jurisdiction over maritime areas and their resources. In the proper defense of these interests, it is important to know this space and its resources, to monitor, protect, and preserve it.

This article will focus on Brazilian interests regarding the Blue Amazon, addressing the Brazilian maritime area and its strategic surroundings from a geopolitical perspective. Thus, it seeks to answer the question: what are the coordinated and collaborative actions of civilian and military actors for the sustainable development of the Blue Amazon? And secondarily, to address what its impacts are in the economic, social, and environmental aspects.

Given that the abundance of strategic natural resources motivates the covetousness of third parties, the issue of the use and protection of these resources must be analyzed strategically (Andrade *et al.*, 2020b). According to Romana (2016, p.15), for a State to be more efficient in its achievements, a strategy is necessary, which "corresponds to the pursuit of maximum effectiveness in the State's action in achieving its critical goals".[1]

According to Vaz (2011), the South Atlantic, which previously occupied a secondary role in the interests of the great powers, has come to occupy a strategic and relevant space in

[1] Free translation by the translator of the original: “correspond[a] à procura da eficácia máxima na ação do Estado na realização dos seus fins críticos”.

the world context due to a new geopolitical positioning of the great powers resulting from the discovery of natural resources with economic value and the increase in trade flows in the region. Brazil considers the countries of South America, the African countries bordering the South Atlantic, and this maritime space, as well as Antarctica, as its strategic environment, that is, an area of priority interest to the country, according to the National Defense Policy (Brasil, 2025).

The countries that share the South Atlantic Ocean, on the American side (South America) and on the African side, have particular issues, some of which differ from those of Brazil, such as Argentina, for example. This country has a sovereignty issue over part of its territory (the Falkland Islands). Or, there's the issue of piracy, among others, currently faced by African countries, especially in the Gulf of Guinea.In the case of Brazil, concern regarding its maritime area relates to security and defense, environmental, commercial, economic, and scientific aspects. Thus, the Brazilian State began to develop projects for the preservation, exploration, monitoring, and defense of this area, such as the Continental Shelf Survey (LEPLAC), the Marine Spatial Planning (PEM), the Antarctic Program (PROANTAR), and the Blue Amazon Management System (SisGAAz), among other examples cited by Santos *et al.* (2022).

The methodology of this work was based on official Brazilian documents and secondary sources, with the purpose of exploring the main geopolitical challenges facing Brazil regarding the Blue Amazon, reinforcing the importance of adequate priorities, investments, means, instruments, and public policies for the surveillance and defense of this area.

The text is divided into five sections. This introduction presents the analytical framework of the subject; the second section presents the riches of the Blue Amazon; the third section outlines some actions that the State is undertaking in this maritime space; and the fourth section discusses cooperation actions with other countries for the South Atlantic. The fifth section concludes the article with its final considerations.

2 THE ECONOMIC, SOCIAL AND ENVIRONMENTAL ASPECTS

The choice of these three dimensions is a simplification, but it is justified by the definition of the concept of sustainable development, enshrined in the Brundtland Report of 1987 and corroborated at the United Nations Conference on Environment and Development (Earth Summit or Rio 92). The three pillars of the principle of sustainable development are

environmental criteria, social justice, and economic viability. In terms of politics and law, it can be interpreted as the balance between the interests of different stakeholders so that the decision can be effectively implemented. In other words, it requires dialogue, transparency, legality, and legitimacy during the decision-making process. With undeniable diversity and complexity, sustainability on a national scale is always an immense challenge, according to Ribeiro *et al.* (2025).

The natural resources are still little known, starting with the rich local biodiversity and the existence of unique ecosystems that provide important services for the maintenance of life on Earth. In a 2010 publication, the Ministry of Environment and Climate Change (MMA) divided the coastal and marine region into several ecosystems, such as dunes, beaches, wetlands and flooded areas, estuaries, coastal sand dunes, mangroves, rocky shores, lagoons and marshes. These ecosystems interact with five terrestrial biomes (Atlantic Forest, Amazon, Caatinga, Pampa, and Cerrado), creating environments that provide unique ecosystem services, as explained in Ipea (2024).

In this context, the interactions between the ocean and the climate constitute an important environmental issue (WMO, 2025), even more so at the time of COP 30 (Conference of the Parties on the climate regime), to be held in Belém do Pará. The ocean can be considered a maintainer of the atmosphere's temperature, since it has a great capacity to retain heat and distribute this balance across the planet through water evaporation and ocean currents. Furthermore, one of the functions of water is to sequester and store carbon from the atmosphere. However, Campos (2014) states that global warming and increased air pollution lead to warming waters, increased melting of polar ice caps, decreased salinity and acidification of waters, rising sea levels and, consequently, changes in ocean currents, altering the ocean-atmosphere balance that provides the conditions for life on Earth.

When considering activities in Brazilian maritime space, some attract more attention than others; however, they cannot be considered more or less important. The first of these is maritime transport, which accounts for more than 95% of Brazilian international trade, according to the Brazilian Navy. Alongside maritime transport, there is the shipbuilding industry, which is also driven by the construction of military vessels. It is also important to consider that maritime transport requires adequate port infrastructure. In addition to infrastructure, the construction of the vessels themselves is now requiring modification, and the most important of these, at the moment, is the decarbonization of the vessels (considered in the

BNDES Azul project in Brazil). Regarding traffic through the South Atlantic, Silva (2014) had already addressed possible changes: the expansion of the Panama Canal; the route through the Arctic; and regional integration routes. However, currently, two more central factors need to be considered: the hyper-competitive geopolitical, economic, and technological rivalry between the governments of China and the United States, as well as the deleterious effects of climate on the navigability of the Panama Canal and the South Atlantic shipping routes.

The second relevant activity is coastal tourism, which, according to Carvalho (2018), is the sector that employs the most people in Brazil. Globally, activity has been growing and is now almost at the level of 2019, before the pandemic (World Bank, 2025). Specifically regarding coastal tourism, the European Commission states that this sector is responsible for the highest gross value added and the largest number of jobs related to the blue economy in Europe (European Commission, 2025).

It is important to highlight another economic and strategic point: communications. Submarine cables pass through the South Atlantic, allowing Brazil to communicate with other continents. The integrity of these cables is fundamental in guaranteeing the flow of data between countries.

Other activities stem from the exploration or exploitation of existing natural resources. According to the National Petroleum Agency's Monthly Oil and Gas Production Bulletin, in February 2025, 97.4% of oil production came from offshore wells, with 78.8% from the pre-salt zone. However, energy production activity in the maritime zone has diversified. There are several studies on the production of renewable energy from the sea, such as offshore wind, tidal power, wave energy, ocean currents, thermal gradients, and salinity energy (EPE, 2014).

Fishing, whether artisanal or industrial, is a significant activity, and after a period without official information from the Brazilian government, some data has recently been published. Although this data does not yet constitute complete statistics, it can be found on the website of the Ministry of Fisheries and Aquaculture. The data refers to Brazil and includes the number of fishermen, whether artisanal or industrial, as well as characteristics such as gender and education level. The number of vessels is specified by size. Aquaculture was also included in the data. It is important to note that the information provided includes data from both inland and marine waters.

Marine mining, including sea salt, ores, rock salt, precious and semi-precious stones, as well as the exploration of polymetallic nodules (deposits of certain types of ores, such as

manganese, cobalt, nickel, and copper on the deep ocean floor), is the most controversial activity in terms of environmental preservation. With the increased search for natural resources in the sea (blue acceleration), the exploration of certain minerals that are mainly involved in the clean energy production process has intensified. However, this exploitation causes degradation to the marine environment which, due to the slow recovery process, can be considered the extraction of a non-renewable resource, such as the extraction of rhodoliths used in the fertilizer production process.

From an environmental standpoint, the overexploitation of ocean resources due to the search for natural resources by various nations has highlighted concerns about the conservation of the marine environment. The accelerated exploitation of these resources can cause imbalances in this uniquely characterized environment, affecting biodiversity and the ecosystem services provided by the ocean, and potentially even impacting the global climate.

With a geopolitical focus on the strategic environment, the Brazilian State, as the main actor, must exercise its power by regulating the use and protection of this maritime space, and to this end it must implement public policies that consider all the factors involved, namely economic, environmental and sovereignty factors. Furthermore, it should be taken into account that a portion of the maritime space has been the subject of a claim before the Commission on the Limits of the Continental Shelf, resulting in an increase in area and consequently increasing the biological and mineral resources to be protected.

3 INITIATIVES FOCUSED ON THE SEA

3.1. SCIENCE, TECHNOLOGY, INNOVATION AND ENVIRONMENT

The aim of this article is not to exhaustively explore all initiatives related to the sea, but rather to demonstrate, through some of them, the complexity of factors, actors, and variables that these policies need to consider. To organize activities (such as scientific research, environmental conservation, and oceanographic monitoring) that are carried out at sea, Brazil develops the Sectoral Plan for Marine Resources (PSRM). It outlines the most relevant actions, along with their respective objectives, goals, products, and sources of funding for their development. In January 2025, the 11th PSRM was approved, which is expected to be in effect until 2027.

With the objective of “establishing the institutional, strategic, normative and regulatory bases that can be used to support the decision-making process related to the use of the sea and its management and conservation, in the public or private sphere”, as established in the XI PSRM, PEM (described in item 5.9) faces the challenge of creating an arena where public and private interests of the various actors in society are weighed, in addition to the various existing and future public policies for the Brazilian maritime space. In this process, it is essential that the Brazilian State remains the main actor and exercises its power in coordinating the activities that take place in maritime space. According to the definition adopted by the Intergovernmental Oceanographic Commission (IOC - UNESCO) cited in Andrade and Carvalho (2025, p. 10), "PEM is a public process of analysis and allocation of the spatio-temporal distribution of human activities in marine areas with ecological, economic and social objectives, generally listed by a political process."[2] PEM must be implemented by 2030, in accordance with an international commitment made by Brazil in 2017 at the II Ocean Conference, promoted by the UN.

To make PEM viable in Brazil, the development of a pilot project is underway. In this project, the continental shelf has been divided into four areas: South, Southeast, Northeast, and North. Initially, the funds are not budgetary, as they come from donations from the National Bank for Economic and Social Development (BNDES) for the bidding processes in the South, Southeast, and North regions, and from resources from the Brazilian Biodiversity Fund (Funbio) for the process in the Northeast region. The Brazilian Navy's website dedicated to the PEM states that the project for the Southern region is the most advanced, currently in the fourth part of the first phase. The Northeast region comes in second place, being in the third stage of the first phase. The Southeast region has already had its project approved and is beginning its implementation. For the North region, there is still no information on its progress.

Regarding the budgetary issue, the 2024-2027 Multiannual Plan (PPA) includes the Ocean, Coastal Zone and Antarctica program in its axis 2 - "Economic development and socio-environmental and climate sustainability". This program's primary objective is "to expand scientific and technological knowledge, conserve biodiversity, and promote the sustainable use of natural resources through the effective management of coastal and marine areas, in order to

[2] Free translation by the translator of the original: “o PEM é um processo público de análise e atribuição da distribuição espaço-temporal das atividades humanas em áreas marinhas com objetivos ecológicos, econômicos e sociais, em geral, listado por processo político”.

advance the country's interests in the ocean, coastal zone, and Antarctica." This topic fits both as a core program in the 2024-2027 PPA and as part of its Cross-Cutting Agenda.

Concurrently, other important actions have been developed to encourage the strengthening of policies for the sea. One of them is the official definition of the ocean economy. The "Ocean GDP" Working Group, composed of representatives from various areas of government, has objectives established by Ordinance 23-MB/MD, dated January 27, 2025, including defining the concept of the ocean economy and developing a methodology for its measurement, among others.

In addition to this technical group, others focused on maritime issues were created, such as the Executive Committees for the Blue Economy and PEM. The Executive Committee “Blue Economy” is coordinated by the Ministry of Science, Technology and Innovation and its main objective is to “plan, develop, maintain and implement a Work Plan, aiming at fulfilling the goals of the “Blue Economy” Action, which are part of the current PSRM (Program for the Development of the Blue Economy). The PEM committee, on the other hand, is composed of 23 members (representatives of public bodies and institutions) and is jointly coordinated by the Ministry of Environment and Climate Change and the Secretariat of the Interministerial Commission for Marine Resources.

In this same context, Brazil, as a participant in the UN's 2030 Agenda, has taken on challenges such as the targets of Sustainable Development Goal (SDG) 14 - Life Below Water and actions related to the Ocean Decade (2021-2030). Within the framework of the 2030 Agenda and the monitoring of SDG 14 targets, on the *odsbrasil* portal, the country developed indicators for only three targets, and for these three, there was a positive performance, according to the National Voluntary Report (Brasil, 2024). Since there are no indicators developed for the others, it is impossible to verify whether or not they are being met. However, this lack of data does not make SDG 14 any less relevant. Beyond the concern for this SDG, it is necessary to emphasize the importance of its interrelationship with the other SDGs. SDG 14 is related in some way to all the other SDGs, demonstrating the importance of the ocean and the blue economy for global sustainable development (Santos, 2022; Barros-Platiau *et al*., 2024).

The Ocean Decade emphasizes ocean science (in its various aspects, such as biological, biotechnological, economic, political, and social, for example) as a driver of sustainable development, combating risks and threats (such as pollution), and integrating

groups of people with a common goal: to better understand the ocean, its interactions with the climate and coastal communities, for example, and its potential.

In Brazil, the Ministry of Science, Technology and Innovation is the "coordinator" of actions related to the Ocean Decade, through the National Implementation Plan for the Decade of Ocean Science for Sustainable Development, which, in turn, is part of the Science at Sea Program. According to Christofoletti *et al.* (2021), as part of the Decade's activities, workshops were held, coordinated by various sectors of society (public, private, international organizations and academia), and with the participation of the population. Brazil has also focused on the education of children and young people, with the ambition of increasing the sensitivity of future decision-makers on ocean issues. In 2025, UNESCO recognized Brazil as the first country to implement blue education in school curricula.

In parallel, the Brazilian Navy is conducting the Sectoral Plan for Marine Resources — currently in its 11th edition — which includes a set of actions focused on maritime issues. In this context, the Navy acts both as a coordinator and as a collaborator with other government agencies, promoting initiatives dedicated to maritime affairs. It is important to highlight the concern of the above initiatives with sustainability, which can be observed in the sustainable development programs, investments in clean energy, and biodiversity conservation programs mentioned above. These concerns are accompanied by a predominant issue: that of sovereignty. According to Medeiros Filho (2022), a strong State is necessary in this process of implementing national strategies within the current framework of a multilateral approach.

3.2. SOME INITIATIVES RELATED TO DEFENSE AND SECURITY

Of the three key documents for Brazil's defense, two directly address the maritime environment. These are: the National Defense Policy - PND (2005, 2018, 2024) and the National Defense Strategy - END (2008, 2024). Both documents recognize the defense and national security of the South Atlantic maritime space as a priority.

Considering the importance of the Blue Amazon, both for its abundance of resources and for its strategic and geopolitical value for national defense, it is essential that the State dedicate special attention to this maritime area, also through public defense policies. From this perspective, the Brazilian Navy has been undertaking efforts through strategic programs aimed at operationalizing actions for the protection and monitoring of the sea. Therefore, it is worth

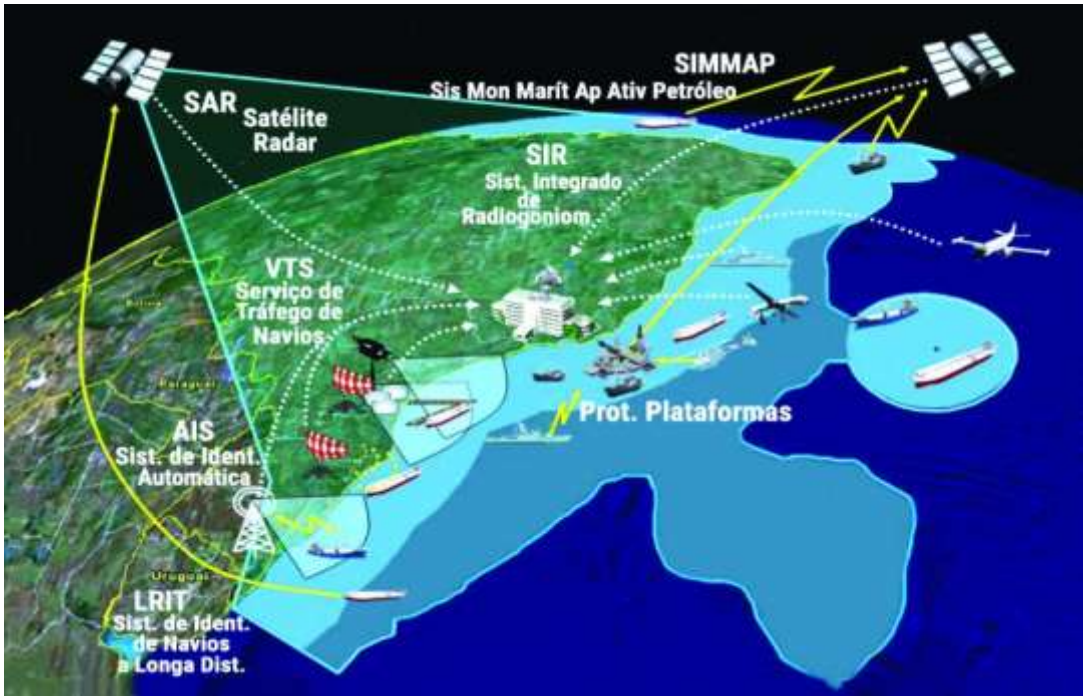
mentioning three strategic programs conducted by the Brazilian Navy directly related to the defense of Brazilian sovereignty in the South Atlantic, as observed below.

According to Andrade, Barros-Platiau and Hillebrand (2020), the Brazilian Navy's Nuclear Program – PNM – has as its priority objective to enable Brazil to master the nuclear fuel cycle and the construction of an onboard nuclear plant (two Navy projects are under this program). This program has a spin-off effect, since the unfolding of this knowledge should reach other sectors of the economy, such as the energy, health, and agro-industrial sectors, according to the Brazilian Navy. Directly related to defense, the program is fundamental for the development of the reactor for Brazil's first nuclear-powered submarine, which is being developed under another Brazilian Navy program, PROSUB.

The second important program for the defense of the Blue Amazon is the Modernization of Naval Power. This program is subdivided into four subprograms: Submarine Development (PROSUB), Tamandaré Class Frigates (PFCT), Acquisition of Hydro-oceanographic Resources (PROHIDRO), and those related to the Marine Corps (CFN), such as PROADSUMUS. These subprograms aimed at strengthening Naval Power have a dynamic effect on the economy, science and technology areas, and Brazilian industry.

As a third important program for the Blue Amazon, we can mention the Blue Amazon Management System (SisGAAz), a supervisory system for monitoring this large area that is the Blue Amazon, developed by the Navy. This system has the mission of "continuously monitoring and protecting maritime areas of interest and inland waters, their living and non-living resources, their ports, vessels and infrastructure, in the face of threats, emergencies, environmental disasters, hostilities or illegalities, in order to contribute to the security and defense of the Blue Amazon and to national development" (as defined by the Brazilian Navy). These activities are carried out by a set of systems that should connect with other Brazilian agencies and institutions such as the Federal Police, Brazilian Institute for the Environment and Renewable Natural Resources (Ibama), the Federal Revenue Service, Petrobras, among others.

Figure 1 - SisGAAz (scheme)



Source: Brazilian Navy.

Furthermore, it is worth mentioning the "Expanding Logistical Support Capacity for Operational Resources" Program, which is being developed with the objective of increasing the defense and security capacity of the Blue Amazon region through the construction of a multi-purpose naval complex at the mouth of the Amazon River. It should be considered that all actions taken by the State to strengthen the supervision, defense, and security of maritime space, including strengthening deterrent power, contribute to a more effective positioning of the country in regional geopolitics.

4 BRAZILIAN INTERACTIONS IN THE SOUTH ATLANTIC

The National Defense Strategy makes it clear, in its item 1, that Brazilian concern is not limited only to the space of Brazilian Jurisdictional Waters and the Area (international space), when it proposes that "to increase this security, it is important to expand an environment of cooperation with countries bordering the South Atlantic, especially through their Navies"[3],

[3] Free translation by the translator of the original: “para o incremento dessa segurança, é importante a ampliação de um ambiente de cooperação com países lindeiros do Atlântico Sul, sobretudo por meio de suas Marinhas”.

in addition to seeking to reduce the possibility of conflicts in the strategic environment, in the maritime case, through the consolidation of the South Atlantic Peace and Cooperation Zone (ZOPACAS).

According to Reis (2011), Brazil's concerns with maritime space are not limited to exclusively Brazilian issues, but also to the international space that separates Brazil from Africa, due to the defensive perimeter, and therefore, under Brazilian maritime power.

Also important for the region are bilateral and multilateral agreements relating to military activity. The United States maintains ships off the African coast, the North Atlantic Treaty Organization (NATO) conducts military exercises in the Cape Verde region, and Russia, off the coast of Venezuela. It is also worth remembering that NATO can access the entire South Atlantic area as a base for its military operations through the United Kingdom's islands located in the region (map 1 below). However, this access to the South Atlantic is currently a political-strategic decision. In 2010, this organization revised its Strategic Concept for the Defence and Security of the members of the North Atlantic Treaty Organization, and declared that its actions are not restricted only to the North Atlantic, but can extend beyond its borders, wherever there is "instability or conflict [...] that could directly threaten the security of the Alliance, especially fueling extremism, terrorism or illicit transnational activities, such as arms, drug and human trafficking" (NATO, 2010, item 11, from the section "The security environment").

Figure 2- British islands in the South Atlantic

Source: Naval Power website http://www.naval.com.br.

The international presence, mainly of other navies, in the region is primarily due to the US Fourth Fleet, focused on operating in the Caribbean and the South Atlantic, and the British Navy, which is present due to the need to protect the islands under its control. The United Kingdom owns several islands in the South Atlantic (Ascension, Saint Helena, Tristan da Cunha, Gough, South Sandwich Islands, South Georgia, South Orkney Islands, and the Falkland Islands).

The geopolitical initiatives of Portugal and Spain in the South Atlantic were demonstrated by Portugal in 2010 with the initiative to include the South Atlantic in NATO's strategic concerns. Spain, in 2009, held a meeting that resulted in the Lanzarote Declaration, which emphasized the need for cooperation between the countries of the South Atlantic area to face geopolitical threats and challenges. In addition to the initiatives of Portugal and Spain, there are several programs developed by the European Union and its constituent countries (such as bilateral agreements) for the regional scope, mainly focused on the African continent (such as, for example, the European Union Maritime Security Strategy and the European Energy Security Strategies).

In the African continent, the Gulf of Guinea has received special attention from Brazil. This maritime area is rich in natural resources, primarily oil. However, despite these resources, the countries in this region are considered Fragile or Failed States according to the Organization for Economic Cooperation and Development's (OECD, 2021) definition, as they have low development indices and high rates of violence. In that region, Brazil is concerned about the high rates of piracy, armed robbery of ships (especially oil tankers), trafficking in human beings, weapons and drugs, terrorism, illegal immigration, illegal fishing, according to Guastini (2020), and the consequent environmental degradation. Brazil, like other countries, individually and/or in groups such as the European Union, has initiatives to support regional development and defense, and the construction of its identity, good governance, and the strengthening of the rule of law. Brazil has several bilateral technical, commercial, social, cultural, and military cooperation agreements with all these countries located in the Gulf of Guinea, in addition to military operations for the training of local forces, such as Guinex-II.

4.1. SOME TREATIES COVERING THE SOUTH ATLANTIC REGION AND THE BRAZILIAN STRATEGIC ENVIRONMENT

Brazil is a signatory to several important international agreements for the Blue Amazon. The first treaty that should be mentioned is the United Nations Convention on the Law of the Sea, which defines territorial sea and contiguous zone, the rules applicable to ships when passing through territorial seas, how resources, living or non-living, seabed and subsoil can be exploited, that is, it defines in general terms how ocean governance "works".

The Treaty of Tatlelolco, signed by Brazil in 1967, deals exclusively with the prohibition of nuclear weapons in Latin America and the Caribbean, allowing the use of nuclear energy for peaceful purposes by these countries. It encompasses the Blue Amazon, when in its article 3, it establishes that the term "territory" includes the territorial sea and other spaces where the country exercises sovereignty. It should also be mentioned that this treaty has two protocols. The first extends the terms of the treaty to countries that have territories in the region. The second protocol concerns the intention of countries that possess nuclear weapons not to use them in this region, or against countries that are signatories to this treaty. Beyond its importance for local and global geopolitics, this treaty is primarily important for the Blue Amazon in terms of prohibiting nuclear testing in the region. It is public knowledge that some nuclear tests have been conducted in maritime zones, destroying biodiversity and affecting coastal populations.

One international initiative that should be mentioned is the creation of the South Atlantic Peace and Cooperation Zone (ZOPACAS), led by Brazil in 1986. It is not a treaty, but an agreement and a forum that seeks to maintain peace and security and regional cooperation among the 24 adhering countries (bordering the South Atlantic). According to item 2 of UN Resolution 41/11 of 1986, the agreement is mainly focused on cooperation between these countries to promote economic and social development, environmental protection, conservation of living resources, and the maintenance of peace and security in the region. According to Queiroz (2023), Brazil is a key player in this multilateral forum. In 2026, the ninth ZOPACAS meeting is expected to take place in Brazil, when it will assume the pro tempore presidency.
The Antarctic Treaty of 1959 defines the area of the Antarctic continent covered by the Treaty (south of the 60°S parallel). The treaty establishes the peaceful use of the continent and the demilitarization of the region, with the main activity permitted on the continent being scientific research by the signatory countries (Mattos, 2014). Although at first glance it may seem out of

context to cite an agreement concerning a continent bordered by another ocean, the Antarctic, since 2012, Antarctica has been considered, by the National Defense Strategy, as part of Brazil's strategic environment and, therefore, an area of its geopolitical interest. In this sense, PROANTAR allows Brazil to maintain its scientific base in Antarctica to carry out various research projects, many of which are funded by the Coordination for the Improvement of Higher Education Personnel (Capes) and the National Council for Scientific and Technological Development (CNPq) , such as the INCT of the Cryosphere, based at the Federal University of Rio Grande do Sul.

In addition to these treaties and the ZOPACAS already mentioned, Brazil is also a signatory to the Mindelo Declaration (2023), which resumes cooperation in the South Atlantic based on the new international order, the Convention on Biological Diversity, and the Nagoya Protocol. Although it has signed the Treaty on Biodiversity Beyond National Jurisdiction (BBNJ), Brazil has not yet ratified it. There are also several bilateral treaties between Brazil and countries bordering the Atlantic, which can be consulted on the Brazilian government's website, on the Concordia portal.

5 CONCLUDING REMARKS

The green and blue Amazon regions share many common characteristics, such as their vast size, enormous biodiversity, and a commitment to promoting sustainable development, in addition to a vital interdependence with climate change. Analyzing the many facets related to the Blue Amazon and regional geopolitics is quite complex and diverse. Beyond the well-known need to control activities in the region to curb predatory patterns of exploitation of land and sea resources, Brazil faces challenges related to the current crisis of international cooperation and multilateralism. Therefore, the link between the State, power, and space requires special attention from the government and its various stakeholders.

Security and supervision of the maritime area are paramount factors with regard to vessel traffic and submarine cable communications. Both activities (supervision and security) are the responsibility of the Brazilian Navy, which, in order to fulfill this mission, has invested especially in the modernization of its fleet, the nuclear program, and the improvement of the SisGAAz. With these programs, the Brazilian Navy can improve the process of obtaining

information for decision-making and, therefore, improve its performance, including in crisis situations. In this sense, strengthening Brazilian naval power is important.

One issue that runs through all these points is how to harmonize economic activities with the more sustainable use of marine resources. To meet this challenge, an instrument that has proven to be efficient is Marine Spatial Planning, which allows for the organization of activities in time and space, as well as the management of conflicts and interests among the various actors. The development of this management tool, which is already underway in Brazil, can point to development promoted by the exploitation of rich living and non-living resources and by activities in the ocean space, without losing sight of the concern for the preservation of the marine environment.

No less important for the ocean, as proposed by the Ocean Decade, is support for scientific projects in the most varied areas of knowledge, as well as blue education, and always in an integrated way. We need to better understand life in the region and train future decision-makers and researchers.

Brazil must maintain its geopolitical focus on the Blue Amazon from both a diplomatic and military perspective, considering the environmental, economic, and social aspects, as discussed in this article. However, it is necessary to deepen the synergy between these approaches so that the leading role of the Brazilian State in the region can be effective and also encourage and improve collaborative actions with neighboring countries. Only a sovereign, well-organized state with effective governance instruments can implement complex actions that combine science, concern about climate change, environmental conservation needs, biodiversity preservation, without losing sight of economic and social development.

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SipamMar: a Brazilian autonomous system for oil spill detection and modeling

SipamMar: um sistema autônomo brasileiro de detecção e modelagem de manchas de óleo

SipamMar: un sistema autónomo brasileño de detección y modelado de manchas de petróleo

SipamMar : un système autonome brésilien de détection et de modélisation des nappes de pétrole

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Abstract
This paper introduces SipamMar, an autonomous Brazilian system designed for the detection and dispersion simulation of oil spills within Brazilian jurisdictional waters. This system aims to enhance the environmental monitoring of the "Blue Amazon," a strategic national asset

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vulnerable to oil spills. SipamMar integrates remote sensing, artificial intelligence, and numerical modeling to establish an automated, operational alert and oil spill simulation framework. Its methodology features automated slick detection in Sentinel-1 Synthetic Aperture Radar (SAR) imagery using a Convolutional Neural Network (U-Net with a ResNet-50 backbone) trained on 8,072 samples. For dispersion modeling, the system employs the Lagrangian MEDSLIK-II model, which is driven by metoceanographic data from Copernicus, ERA5, and GFS/NOAA. To validate detections and minimize false positives, auxiliary environmental data — including wind, chlorophyll, currents, and temperature — are incorporated. Case studies have demonstrated the system's capability to effectively identify oil slicks with a high degree of probability (>80%) and simulate their trajectories within an operational timeframe. SipamMar marks a significant advancement in environmental emergency response, with future work focused on *in-situ* validation and operational expansion for continuous improvement.

Keywords: Oil Spill; Blue Amazon; Remote Sensing; Artificial Intelligence; SAR.

Resumo

O presente artigo descreve o SipamMar, um sistema autônomo brasileiro de detecção e simulação da dispersão de manchas de óleo em águas jurisdicionais brasileiras, visando contribuir para o monitoramento ambiental da Amazônia Azul – patrimônio estratégico e vulnerável a derramamentos de óleo. O sistema integra sensoriamento remoto, inteligência artificial e modelagem numérica para criar um sistema operacional automatizado de alerta e simulação da dispersão de óleo em águas brasileiras. A metodologia inclui detecção automatizada de manchas, por Redes Neurais Convolucionais (U-Net com ResNet-50), em imagens de Radar de Abertura Sintética (SAR) do Sentinel-1, treinadas com 8.072 amostras. A modelagem da dispersão utiliza o modelo Lagrangeano MEDSLIK-II, alimentado por dados meteoceanográficos do Copernicus, ERA5 e GFS/NOAA. Dados ambientais auxiliares (vento, clorofila, correntes e temperatura) são usados para validar detecções e reduzir falsos positivos. Os estudos de caso demonstraram a capacidade do sistema em identificar manchas com altas probabilidades (>80%) e simular suas trajetórias, com um tempo de processamento operacional. O SipamMar representa um avanço significativo na resposta a emergências ambientais, com perspectivas de futuras validações *in-situ* e expansão operacional para otimização contínua.

Palavras-Chave: óleo; Amazônia Azul; Sensoriamento Remoto; Inteligência Artificial; SAR.

Resumen

El presente artículo describe SipamMar, un sistema autónomo brasileño para la detección y simulación de la dispersión de manchas de petróleo en aguas jurisdiccionales brasileñas, con el objetivo de contribuir al monitoreo ambiental de la Amazonia Azul, un patrimonio estratégico vulnerable a los derrames de petróleo. El sistema integra teledetección, inteligencia artificial y modelado numérico para crear un sistema operativo automatizado de alerta y simulación de la dispersión de petróleo en aguas brasileñas. La metodología incluye la detección automatizada de manchas, mediante Redes Neuronales Convolucionales (U-Net con ResNet-50), en imágenes de Radar de Apertura Sintética (SAR) del Sentinel-1, entrenadas con 8.072 muestras. El modelado de la dispersión utiliza el modelo Lagrangiano MEDSLIK-II, alimentado por datos meteoceanográficos de Copernicus, ERA5 y GFS/NOAA. Se utilizan datos ambientales auxiliares (viento, clorofila, corrientes y temperatura) para validar las detecciones y reducir los falsos positivos. Los estudios de caso demostraron la capacidad del sistema para identificar

manchas con altas probabilidades (>80%) y simular sus trayectorias en un tiempo de procesamiento operacional. SipamMar representa un avance significativo en la respuesta a emergencias ambientales, con perspectivas de futuras validaciones *in situ* y expansión operativa para una optimización continua.

Palabras Clave: petróleo; Amazonia Azul; Teledetección; Inteligencia Artificial; SAR.

Résumé
Cet article décrit SipamMar, un système autonome brésilien de détection et de simulation de la dispersion des nappes d'hydrocarbures dans les eaux juridictionnelles brésililiennes, visant à contribuer à la surveillance environnementale de l'Amazonie Bleue – un patrimoine stratégique vulnérable aux déversements de pétrole. Le système intègre la télédétection, l'intelligence artificielle et la modélisation numérique pour créer un système opérationnel automatisé d'alerte et de simulation de la dispersion des hydrocarbures dans les eaux brésiliennes. La méthodologie comprend la détection automatisée de nappes par des Réseaux de Neurones Convolutifs (U-Net avec ResNet-50) sur des images de Radar à Synthèse d'Ouverture (RSO) de Sentinel-1, entraînées avec 8 072 échantillons. La modélisation de la dispersion utilise le modèle Lagrangien MEDSLIK-II, alimenté par des données météo-océanographiques de Copernicus, ERA5 et GFS/NOAA. Des données environnementales auxiliaires (vent, chlorophylle, courants et température) sont utilisées pour valider les détections et réduire les faux positifs. Les études de cas ont démontré la capacité du système à identifier les nappes avec de fortes probabilités (>80%) et à simuler leurs trajectoires dans un temps de traitement opérationnel. SipamMar représente une avancée significative dans la réponse aux urgences environnementales, avec des perspectives de validations futures *in situ* et d'expansion opérationnelle pour une optimisation continue**.**

Mots-clés: pétrole ; Amazonie Bleue ; Télédétection ; Intelligence Artificielle ; RSO.

1 INTRODUCTION

Brazil's coastline, stretching over 7,400 kilometers and encompassing 5.7 million km² of Exclusive Economic Zone, nicknamed the "Blue Amazon," constitutes a national asset of strategic interest, both from an economic and national sovereignty perspective, as well as an ecological one. Economically, the Blue Amazon is responsible for 95% of the national oil production and 83% of natural gas production (Andrade; Franco, 2018). Furthermore, from a logistical and commercial standpoint, this immense region contains Brazil's main access routes to global trade. As highlighted by Admiral Eduardo Bacellar Leal Ferreira in 2017, these maritime routes are responsible for 97% of Brazilian foreign trade and more than 90% of the country's communications (Andrade; Franco, 2018).

Not only that, the Blue Amazon also harbors large reserves of minerals crucial for the manufacture of modern technologies, such as rare earth elements (REEs), manganese, iron,

cobalt, among others (Pessoa, 2015). The recent Brazilian claim to the Rio Grande Rise demonstrates the mineral exploration potential of the Blue Amazon (Silva, 2021). On the other hand, maritime traffic and marine resource exploration activities can compromise the marine environment, making this region vulnerable to various activities harmful to the marine ecosystem, such as marine pollution (Barbosa Júnior, 2012). The vulnerability of this vast region to oil spill events was dramatically highlighted by the spill that occurred in northeastern Brazil in 2019, which affected more than 2,800 km of coastline, impacting fragile ecosystems and causing serious socioeconomic and health effects in 11 Brazilian states (Soares *et al.,* 2022; De Moura; Polito, 2022).

The event, to date the largest ever recorded in tropical regions, exposed deficiencies in national environmental surveillance, alert, and response systems (Magris; Giarrizzo, 2020). Given this reality, improving the capacity to monitor and respond to these environmental disasters has become an urgent necessity to preserve the Blue Amazon and the country's coastal regions. However, monitoring the Blue Amazon is challenging, as it faces budgetary and personnel constraints, making surveillance and response capabilities logistically inefficient, relying solely on traditional naval patrol resources.

In this context, the use of remote sensing through satellite imagery has the potential to expand monitoring capacity in this vast area. The use of Synthetic Aperture Radar (SAR) images, for example, allows the detection of objects and events in the ocean without the need for illumination and favorable weather conditions, typical of optical sensors (Mityagina; Lavrova, 2018; Brekke; Solberg, 2005). On the other hand, the quantity of images available and the need for trained technical personnel restrict the use of these technologies to a few professionals.

Faced with these challenges, machine learning (ML) offers tools for the development of autonomous detection and monitoring systems. In simplified terms, ML consists of the ability of computers to reproduce human intellectual operations through algorithms, such as convolutional neural networks, allowing computers to perform tasks that would typically require human intelligence, including learning, reasoning, and decision-making in a short period of time (Ortiz Valadez *et al.*, 2024). In the field of ML, this branch is dedicated to creating systems that learn from data, identify patterns, and make decisions with little or no human intervention (Ortiz Valadez *et al.*, 2024). This unsupervised learning capability is essential for handling large volumes of data generated by remote sensing equipment, such as SAR images.

Deep Learning (DL) is a specialized branch of ML that uses multi-layered neural networks (deep neural networks) to analyze complex data structures (Bhattacharyya *et al.*, 2020). Deep Learning techniques are especially effective in areas with high-dimensional data, such as speech and image recognition, as they allow the model to autonomously identify the features needed to classify or predict from raw data (Lemley *et al.*, 2017). Convolutional Neural Networks (CNNs), for example, which excel in computer vision tasks, are used for object detection in SAR images.

In this context, in order to assist in the environmental monitoring of the Blue Amazon, the project entitled "Research for the Development of an Autonomous System for Oil Detection and Monitoring in the Ocean" was formalized through a Decentralized Execution Agreement between the Management and Operational Center of the Amazon Protection System (CENSIPAM) and the Federal University of Bahia (UFBA). The overall objective of this project is to integrate remote sensing, machine learning, and numerical modeling technologies to design an automated operational system for alerting and simulating the dispersion of oil spills in Brazilian jurisdictional waters: SipamMar. This article presents the architecture of the developed system, highlighting the methodological advances applied to automatic detection by convolutional neural networks and to the predictive modeling of contaminant trajectories. Finally, a typical case study is presented to demonstrate the application of SipamMar as a coastal environmental monitoring system.

2 RELATED WORKS

2.1 MACHINE LEARNING: SPILL DETECTION IN SAR IMAGES

Machine learning is an effective tool to aid in the detection of oil spills in the ocean, especially when combined with Synthetic Aperture Radar (SAR) imagery. SAR technology is advantageous for oil spill detection due to its ability to capture images regardless of weather and lighting conditions (sunlight), enabling continuous ocean monitoring (Topouzelis, 2008).

A number of machine learning-based techniques have been proposed to improve the detection and classification of oil spills in SAR images. For example, DL networks such as ShuffleNet have been used to increase the accuracy of oil spill segmentation in SAR images and reduce speckle noise (inherent to SAR technology) in different cases (Aghaei *et al.*, 2022).

On the other hand, deep networks, such as stacked autoencoders and deep belief networks, have already been used to optimize and classify oil spills more accurately by

extracting and refining polarimetric SAR features (Chen *et al.*, 2017). Furthermore, advanced techniques incorporating comprehensive algorithms can also be applied. These techniques combine dark spot detection in the image, feature extraction, and classification to differentiate between oil spill events and similar phenomena with greater precision (Raeisi *et al*., 2018).

One technique used, among others, to improve this detection process is the use of fuzzy logic algorithms. The purpose of this algorithm is to improve the classification probabilities of oil spills in relation to lookalikes, which are features in the image that resemble oil spills in SAR images, also known as "false positives". This methodology presents a more convenient method for operational purposes, although natural features can still hinder detection (Liu *et al.*, 2010). Therefore, the integration of LM models with SAR images is a suitable and promising methodology for the detection and monitoring of oil spills in the ocean.

2.2 RESTRICTIONS AND DIFFICULTIES IN OIL SPILL DETECTION USING SAR IMAGING

The use of SAR imagery has emerged as an effective tool for monitoring and identifying oil spills, due to its ability to operate in adverse weather conditions and during the day or night. However, despite its advantages, the use of SAR faces restrictions and limitations that can affect its accuracy and reliability.

One of the main difficulties in using SAR for this purpose lies in differentiating oil spills from natural phenomena that present similar visual characteristics, such as biogenic films, calm waters, whirlpools, or areas of low wind speed. These "false positives" (lookalikes) can lead to classification errors and compromise the effectiveness of detection (Liu *et al*., 2010; Zakzouk *et al.*, 2025). It is possible to minimize false positive cases through fuzzy logic algorithms or probabilistic approaches (Liu *et al.*, 2010; Nirchio *et al.*, 2005).

The spatial and temporal resolution of SAR satellites plays a critical role in the detection and monitoring of oil spills. High-resolution SAR images and the imaging of large areas make the large-scale use of SAR technology expensive. For this reason, SAR images are obtained from free sources, such as the Sentinel constellation of the European Space Agency (ESA). Images from the Sentinel-1 satellite, for example, provide a spatial resolution of 10 meters and a revisit capability restricted to 6 days (Zakzouk *et al.*, 2025). Furthermore, the imaging region covered by the satellite is controlled by other organizations, which limits the area effectively monitored.

Finally, speckle noise is an inherent characteristic of SAR imaging caused by the coherent nature of radar signals. This noise, also known as the "salt-and-pepper effect/noise," manifests as granular interference in images that can obscure the image. Although speckle noise is minimized, it still interferes with SAR images (heterogeneous backgrounds and blurred edges), hindering the segmentation and accurate detection of oil spills (Aghaei *et al.*, 2022). These limitations and challenges highlight the continued need to improve analytical methods, as well as the use of complementary data to increase the reliability and accuracy in oil spill detection using SAR technology.

3 METHODOLOGY

3.1 GENERAL SYSTEM ARCHITECTURE

The developed system consists of two main modules: (a) automated detection of oil spills from SAR images, and (b) numerical modeling of oil dispersion based on meteo-oceanographic data and physicochemical characteristics of the oil. Both modules are integrated by automated routines for acquisition, pre-processing, post-processing, simulation, and visualization of results, operating in replicated environments on the CENSIPAM and UFBA servers.

3.2 DETECTION VIA CONVOLUTIONAL NEURAL NETWORKS

Oil spill detection was performed by implementing classifiers based on the U-Net architecture, commonly used in medical image classifiers (Zhou, 2018), and the ResNet-50 architecture as a backbone embedded in the SipamMar platform.

The model was trained using a dataset composed of IW SLC products from the Sentinel-1 A and B satellites, containing cases of possible oil spills in the ocean. These products were compiled by the team at the Satellite Oceanography Laboratory (LOS) of the Federal University of Bahia (UFBA). The raw data were provided by the European Space Agency (ESA), while the identification and validation of spills—confirmed or with a high probability—was carried out using the Sentinel Vision portal and the Marine Pollution Surveillance Report platform, maintained by OSPO (Office of Satellite and Product Operations).

Although the database is constantly expanding, the results presented in this work used a total of 82 Sentinel-1 A and B products. These products were labeled and subsequently cropped into small square images. For this study, only one set of 512 × 512-pixel images was

used, totaling 8,072 samples, half of which showed oil and the other half did not. The evaluation strategy adopted was the *holdout*, with an 80% split for training and 20% for validation.

To avoid overfitting, several regularization techniques were applied, including an L2 (weight decay) penalty with a value of 10^{-2}, and a 10% dropout, inserted in specific layers of the network.

Additionally, the Early Stopping technique was used, which automatically interrupts training if validation loss fails to improve for a certain number of epochs—in this case, a patience of 14 epochs. This technique directly impacts the loss curve, as it can end training before the model enters overfitting, preventing validation loss from forming the typical U-shaped curve. Thus, training is terminated at the point of best validation performance, without allowing the loss to increase again.

Not only that, but the FocalLoss loss function, appropriate for handling imbalances between classes, was also used in the training. The chosen optimizer was Adam, with an initial learning rate of 10^{-5}. A ReduceLROnPlateau type scheduler was also used, which monitors validation loss and automatically reduces the learning rate when the metric shows stagnation or worsens. The patience factor for the scheduler was set to four epochs. This strategy impacts the loss curve by smoothing the descent and contributing to better convergence, even in regions of little variation.

Regarding the programming language, Python was used, with the PyTorch library as the main framework. PyTorch offers native integration with CUDA technology, allowing the use of NVIDIA GPUs to accelerate operations. In this case, two NVIDIA GeForce RTX 3060 cards were used, each with 12 GB of VRAM. The batch size was adjusted based on the available memory limitation, resulting in an approximate value of 18 samples per batch. This number may vary depending on the size of the images, memory usage by other processes, and other factors of the execution environment.

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Table 1 - Performance metrics of the U-Net detection model with ResNet-50 as backbone

	LOSS	ACC	PRECISION	RECALL	F1	JACCARD
TRAINING	0.002967	0.999546	0.949419	0.950116	0.949466	0.901332
VALIDATION	0.003385	0.996541	0.950338	0.852389	0.897334	0.815822

Source: Designed by the authors, 2025.

The classifier output is a georeferenced probability mask which, upon exceeding defined thresholds, triggers alerts via email and FTP, accompanied by auxiliary environmental data (e.g., currents, winds, and chlorophyll concentration). Operationally, the complete processing time, from image acquisition to alert issuance, is approximately 25 minutes.

3.3 NUMERICAL MODLING WITH MEDSLIK-II

After the detection of the oil slicks in SAR, the trajectory and transformation of the oil were simulated with MEDSLIK-II, a Lagrangian model widely used for short-term forecasting of sea surface spills due to its robustness, ability to represent different types of oil, and ease of coupling to ocean circulation models (De Dominicis *et al.*, 2013a; 2013b). In MEDSLIK-II, the spill representation combines deterministic processes (advection/diffusion forced by currents and wind) and stochastic processes (random walk associated with turbulent diffusivity), in addition to wind drift and, when configured, Stokes drift associated with the wave field (De Dominicis *et al.*, 2013a).

The model's internal structure organizes the state variables into three interconnected groups: (i) "spill" type variables, which control the volume balance in the thick and thin layers at the surface and subsurface, on which weathering processes act; (ii) "particle" type variables, which carry position, volume (with evaporative and non-evaporative parts) and status (surface, dispersed, sedimented or on shore), responsible for transporting oil in the stream field; and (iii) "structural" variables, which express the concentrations at the surface, in the column and on the shore, used in the generation of spatial products (De Dominicis *et al.*, 2013a). Weathering processes (evaporation, emulsification, dispersion/upwelling, and spreading) follow the family of classic oil fate algorithms, with parameters dependent on wind at 10 m and sea surface temperature (SST), and beaching with residence times adjusted to the type of coast (Mackay et al., 1980; De Dominicis *et al.*, 2013a).

In the operational version of SipamMar, environmental inputs are obtained from consolidated operational sources such as Copernicus Marine Service (current and SST fields), ERA5 and GFS/NOAA (wind), and integrated by Python routines for automated download

(motuclient, cdsapi and requests), pre-processing (standardization/grid, formatting compatible with MEDSLIK-II in NetCDF) and visual validation of forcing factors. This automation also drives the post-processing stage, standardizing the generation of maps and animations and reducing manual intervention during operation, as described in its pipeline (De Dominicis *et al.*, 2013b).

In our operational setup, each simulation is initialized with 100,000 Lagrangian particles distributed over the detection polygons, a solution that offers good spatial resolution of the simulated concentrations and is within the range recommended/validated in the MEDSLIK-II literature itself (De Dominicis *et al.*, 2013a; 2013b). The kinematics are integrated with a fixed time step for transport, while weathering processes use a shorter internal sub-step, according to the model formulation; thus, stability and accuracy control is achieved by choosing the steps and diffusion coefficients (De Dominicis *et al.*, 2013a).

The numerical tolerance of the MEDSLIK-II solver covers the spatial resolution of the oil tracer grid, the time steps, and the diffusion coefficients used. For realistic concentration reconstruction, the oil tracer grid resolution is approximately 100 meters. This resolution is calibrated to be between the diffusion scale (approximately 60 meters) and the advective scale (approximately 180 meters), considering a Lagrangian time step of 1800 seconds (30 min) and a horizontal diffusivity coefficient of 2 m^2/s, consistent with high-resolution Eulerian models (De Dominicis et al., 2013a). The vertical diffusivity coefficients (Kv) are 0.01 m^2/s within the mixing layer and $1x10^{-4}$ m^2/s below it, respectively (De Dominicis *et al.*, 2013b).

The diagnostic outputs of our system are stored in NetCDF every 1 hour, ensuring compatibility with the forcing and the routine for disseminating the results; When necessary for communication, cartographic products are aggregated into wider windows without altering the internal temporal resolution of the calculation (De Dominicis *et al.*, 2013b). The deterministic terms of surface displacement include the contribution of ocean model currents, a wind correction (applicable as an uncertainty term when surface circulation is not fully resolved), and, when enabled, Stokes drift parameterized from the JONSWAP wave spectrum (Hasselmann *et al.*, 1973; De Dominicis *et al.*, 2013a). For latitudes greater than 10°S, a wind drift factor of 6% and an angle of 45° are used, as these were considered the most effective for reproducing the trajectory observed in Brazilian waters, differing from the typical values (1-6% for the factor and 0-25° for the angle) found in other regions such as the Mediterranean wind (Correia Lima *et al.*, 2025).

Together, this configuration closes the operational chain: ingestion of SAR data and automatic detection; preparation of forcings; Lagrangian simulation with weathering and

interaction with the coast; and GIS-ready export (NetCDF and vector layers), which supports the rapid analysis and reproducibility of the system flow, a central foundation of the use cases presented. This makes them crucial tools for supporting decision-making in environmental response and in planning actions to mitigate and prevent oil spills at sea.

The complete automation of the process – from configuration to figure generation – was consolidated by scripts, significantly reducing human intervention and execution time, as well as minimizing configuration errors. The execution time was approximately 20 minutes.

4 DEVELOPMENT

4.1 OPERATIONAL INTEGRATION

The system already operates with automatic Sentinel-1 image ingestion capabilities, neural network analysis, alert transmission, and activation of the ocean modeling module. Meteorological and oceanographic data are acquired programmatically, and simulations are run considering multiple oil types (light, medium, and heavy), with daily graphical outputs and hourly animations for each type.

The decision to run the model for three different oil types was made assuming a lack of API information for the spilled oil, which is quite common in Brazilian basins. This type of information is not openly shared due to "sensitive" issues alleged by operators in Brazilian waters. However, with the specific API, only one simulation is performed. The interoperability of the system outputs with GIS environments allows the generation of analytical products with explicit spatial support, which are fundamental for environmental response and the planning of mitigation and prevention actions.

4.2 CASE STUDY 1: SOUTHWESTERN PORTION OF THE GULF OF MEXICO

To demonstrate the applicability of the developed system, an episode of detection of a possible oil spill identified by Sentinel-1 SAR imagery was selected. These coordinates correspond to the southwestern portion of the Gulf of Mexico, near the coast of the state of Veracruz (Mexico), and the maritime region between the Bay of Campeche and the southern coast of the state of Tamaulipas. This case study illustrates the complete functioning of the operational chain – from image ingestion, through automatic detection, to dispersion simulation and visualization of potential impacts.

Figure 1 - Metadata for the Sentinel-1 SAR image (CC57 orbit) used for automated detection in the Gulf of Mexico

Coord. Range	Minimum	Maximum
Latitude	20.3953	22.505
Longitude	-95.6758	-92.9202

- Input title: `S1A_IW_SLC__1SDV_20200203T002425_20200203T002453_031081_039239_CC57`
- Input path: `/host/mnt/camobi_process/rioss_outputs/prod/data/4dd90752-d616-55df-b420-dc1d35691bd8/preproc_sar/4dd90752-d616-55df-b420-dc1d35691bd8.nc`

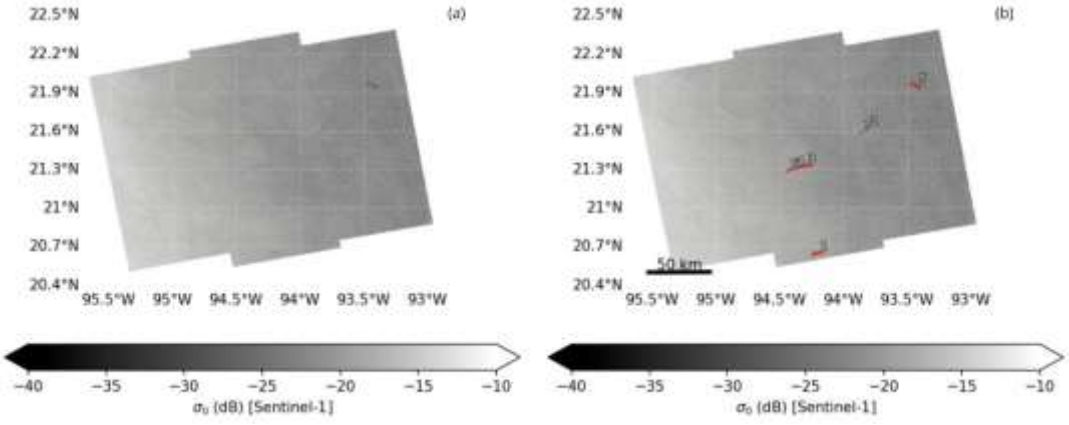
Source: SipamMar.

4.2.1 Automated detection

The analyzed SAR image was processed by the SipamMar system, trained with U-Net type convolutional neural networks. Figure 2 shows, in panel (a), the georeferenced Sentinel-1 SAR image (σ_0 in dB) of the southwestern Gulf of Mexico region, without indications of detection, while panel (b) shows the results of the automatic segmentation performed by the SipamMar system.

The spills identified as probable oily features are highlighted with red outlines and numbered according to their respective detection probabilities. Detections occur in areas with low backscattering ($\sigma_0 < -25$ dB), consistent with the suppression of surface roughness caused by oil films. The comparison between the two panels highlights the system's ability to automatically identify suspicious regions in complex SAR images, even over a wide spatial extent and under gradual variation in sea roughness.

Figure 2 - Post-processed and georeferenced CC57 SAR images at σ_0 (Sigma_zero, in dB). (a) SAR image without detections; (b) SAR image with system detections, marked in red



Source: SipamMar

Figure 3 presents the output table of the automatic detection model of the SipamMar system, containing metadata for seven polygons segmented as possible oil spills in the ocean. For each detection, the geographic coordinates (latitude and longitude of the centroid), the estimated area (in km²), the average probability of detection, and the highest probability located within the spill are provided. The average probability values vary between 44% and 60%, with local maximums reaching 84%, indicating different levels of confidence in the detections, with polygon 1 being the most relevant from an operational point of view. The presence of links for quick look allows visual validation of the identified features, reinforcing the integration between automatic processes and analysis by experts. This data is crucial for prioritizing inspections and triggering numerical dispersion modeling.

Figure 3 - Metadata from automatic detections performed by the SipamMar system, indicating location, area, average and maximum probability of oil presence for seven polygons identified in SAR Sentinel-1 imagery

	Latitude	Longitude	Area (km²)	Probability	Highest Probability	Quicklook
1	-94.2051	20.6499	4.234	60%	84%	link
2	-93.8101	21.6269	1.344	53%	79%	link
3	-94.3017	21.3299	2.36	52%	77%	link
4	-94.3912	21.3079	1.558	49%	76%	link
5	-93.4262	21.9534	3.596	47%	77%	link
6	-94.4386	21.2905	0.522	46%	75%	link
7	-93.863	21.5869	0.434	44%	65%	link

Sourse: SipamMar

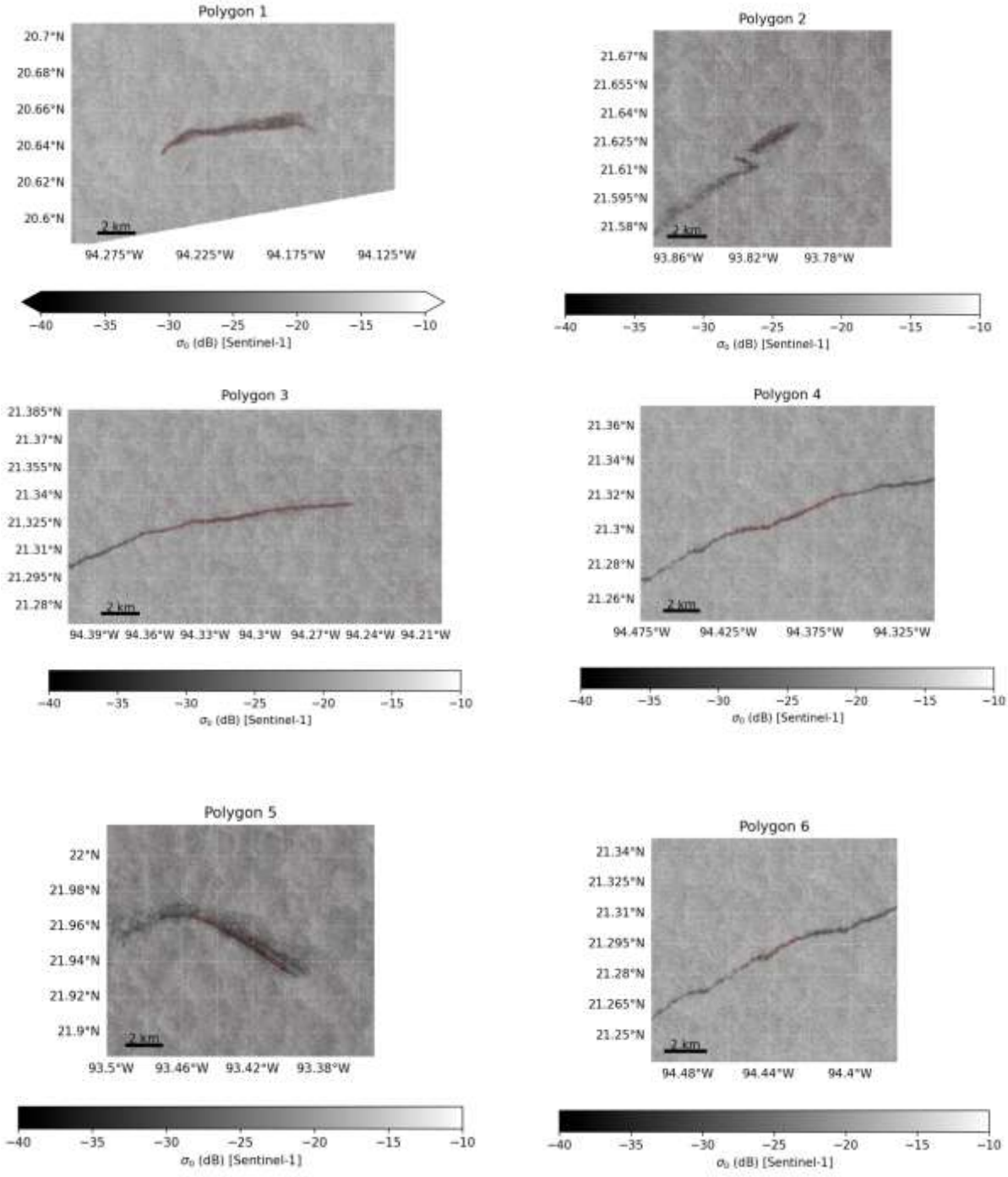
The network provides two confidence metrics: the average probability of detection across the entire spill and the highest probability located at some point within it. Average probabilities range from 44% to 60%, while maximum values reach up to 84%, strongly suggesting the presence of oil in certain regions. It is important to note that the system only issues alerts when the average probability of detection exceeds the threshold previously defined by the operator, ensuring greater robustness and reducing the emission of false positives.

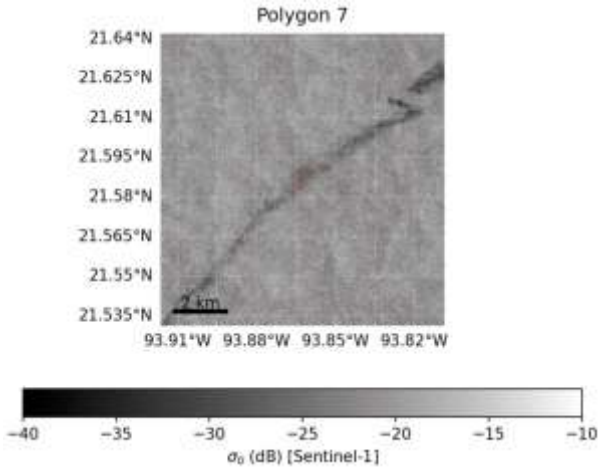
This data is fundamental for prioritizing field verification actions and for feeding modeling systems of the potential contamination trajectory. Figure 4 shows enlarged cutouts of the identified spills, highlighting well-defined contours and distinct signatures that corroborate the hypothesis of oily contamination. The classification was based on a probability greater than 0.6, a threshold calibrated based on performance metrics of the models in previous campaigns.

Figure 5 represents auxiliary environmental variables that comprise the dataset supporting the validation of automatic oil spill detections performed by the SipamMar system.

The first image shows the chlorophyll-a concentration (mg/m³), revealing low levels in the detection area (values < 1 mg/m³), which reduces the probability that the dark patterns in the SAR image are caused by biogenic films associated with algal blooms. The second figure shows the surface wind speed, with a predominance of values between 5 and 7 m/s, which characterizes conditions favorable to the formation of roughness patterns and the passive dispersion of oil at the air-sea interface.

Figure 4 - Excerpts of the oil slicks, from the CC57 image, detected by the system

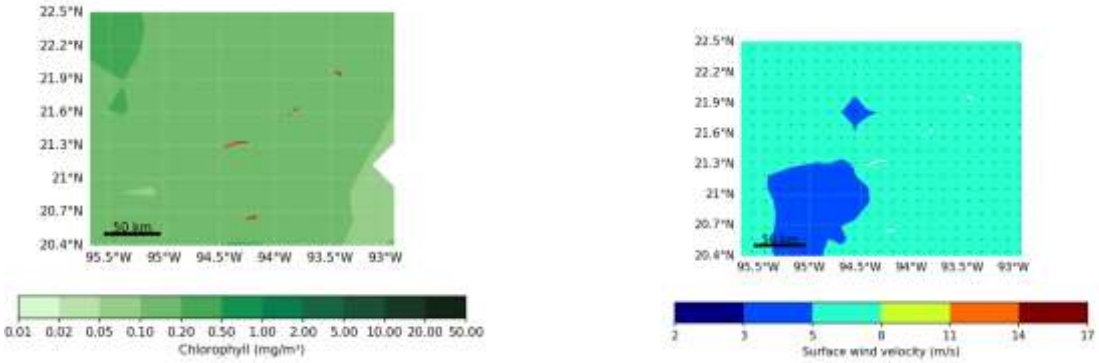


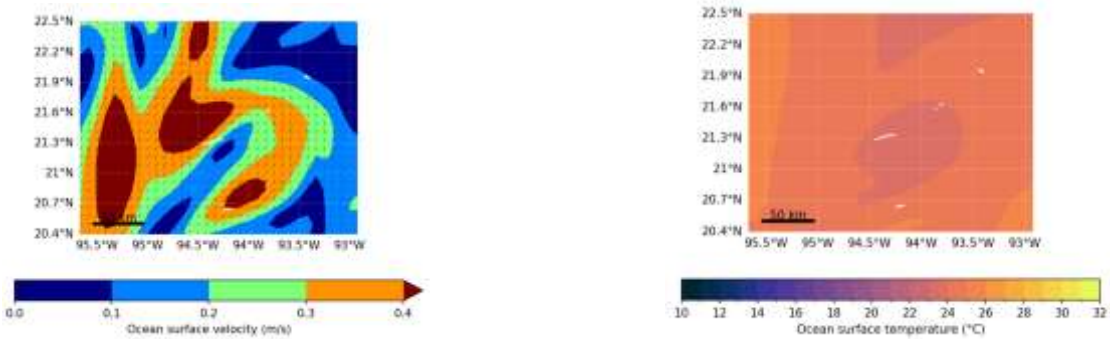


Source: SipamMar.

In the third figure, the speed of surface currents shows regions with intense dynamic activity (values greater than 0.3 m/s), directly influencing the trajectory and fragmentation of the oil slick. Finally, the fourth image shows the sea surface temperature (SST), with homogeneous values between 27°C and 29°C, indicating regional thermal stability. This complementary data is essential for the operator's critical evaluation, allowing them to rule out false detections caused by natural artifacts, confirm the physical consistency of the detected anomalies, and realistically feed oil spill dispersion prediction models.

Figure 5 – Environmental data supporting the validation of oil detections performed by the SipamMar system: (a) chlorophyll-a concentration (mg/m³), (b) surface wind speed (m/s), (c) surface ocean current speed (m/s), and (d) sea surface temperature (°C). These variables support the operator's analysis, helping to distinguish real oil slicks from natural artifacts





Source: SipamMar.

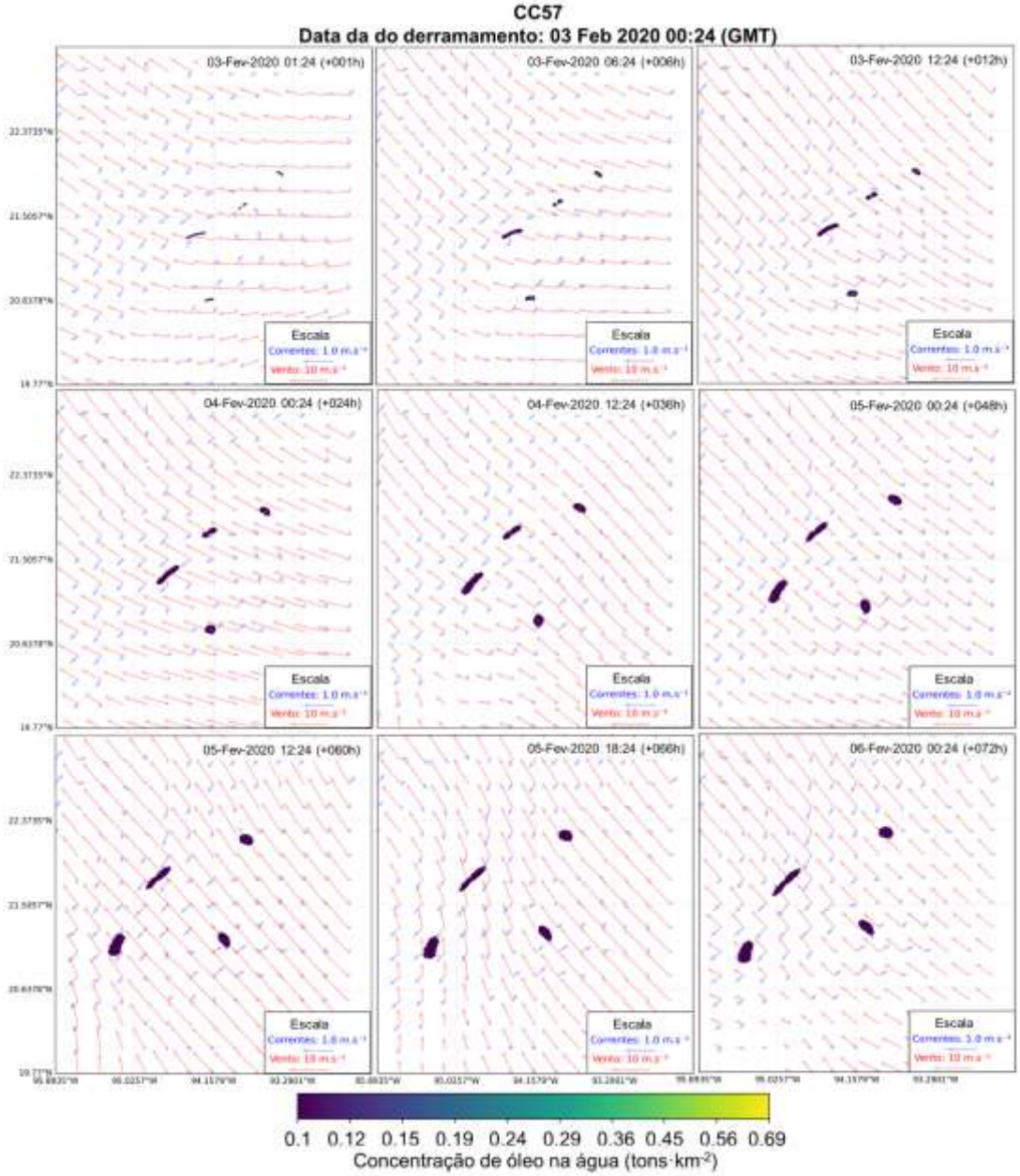
Chlorophyll, for example, can indicate the presence of biological blooms that alter the characteristics of the sea surface. Conversely, the absence of wind or the presence of pronounced thermal gradients can result in patterns similar to oil spills. Thus, integrating this information into the screening process significantly reduces the incidence of false positives, providing more reliable data to decision-makers and optimizing the targeting of response actions.

4.2.2 Dispersion modeling

After confirmation of the detection, the numerical modeling module was activated. Using the modified MEDSLIK-II model, 72 hours of dispersion were simulated, considering medium-type oil, under oceanographic and meteorological conditions extracted from the Copernicus Marine Environment Monitoring Service (CMEMS) and ERA5. Figure 3 shows the temporal evolution of the oil plume, highlighting intervals from 9 to 50 hours after the initial detection.

The simulated trajectory (Figure 6) showed drift consistent with regional current and wind patterns, with displacement mainly to the west, following the direction of surface transport in the area. The plume remained cohesive until about 30 hours, at which point it began to elongate and fragment, indicating an intensification of diffusion and dispersion processes.

Figure 6 - Simulation of the dispersion of the stains identified by the system. Time interval between 9 and 50 hours after identification



Source: MEDSLIK-II.

4.2.3 Operational analysis

This experiment serves as a basis for testing the system's ability to provide, in an integrated and autonomous manner, detection alerts and realistic projections of the spatial evolution of oil spills. The simulated data were exported in formats interoperable with GIS systems (NetCDF, GeoTIFF, and shapefiles), allowing overlay with socio-environmental layers and direct support for decision-making. Furthermore, the performance of the detection model and the consistency of the simulation with expected patterns demonstrate that the system is

applicable not only to historical events but also as a predictive tool in surveillance and rapid response operations.

4.3 CASE STUDY 2: NORTHCENTRAL PORTION OF THE GULF OF MEXICO

In order to demonstrate the applicability of the developed system in detecting oil targets on the ocean surface, with the presence of false positives, a detection episode located in the north-central portion of the Gulf of Mexico, south of the Louisiana coast (USA), was selected. This is an area quite close to offshore oil fields such as Mississippi Canyon and Green Canyon, regions historically associated with oil exploration, including near the site of the Deepwater Horizon disaster (2010), identified by Sentinel-1 SAR imagery.

Here we find an example of a spill surrounded by several cases of false positives such as low wind, close to the oil slick, and rain cells in the upper right corner of the image. This study illustrates the complete functioning of the SipamMAR operational chain, from image ingestion, through automatic detection, to dispersion simulation and visualization of potential impacts. Figure 7 represents the metadata of the analyzed image, with the boundary edges of the original satellite image.

Figure 7 – Metadata from the Sentinel-1 SAR image associated with the oil spill detected in the case study

Coord. Range	Minimum	Maximum
Latitude	27.9048	29.9471
Longitude	-91.1185	-88.203

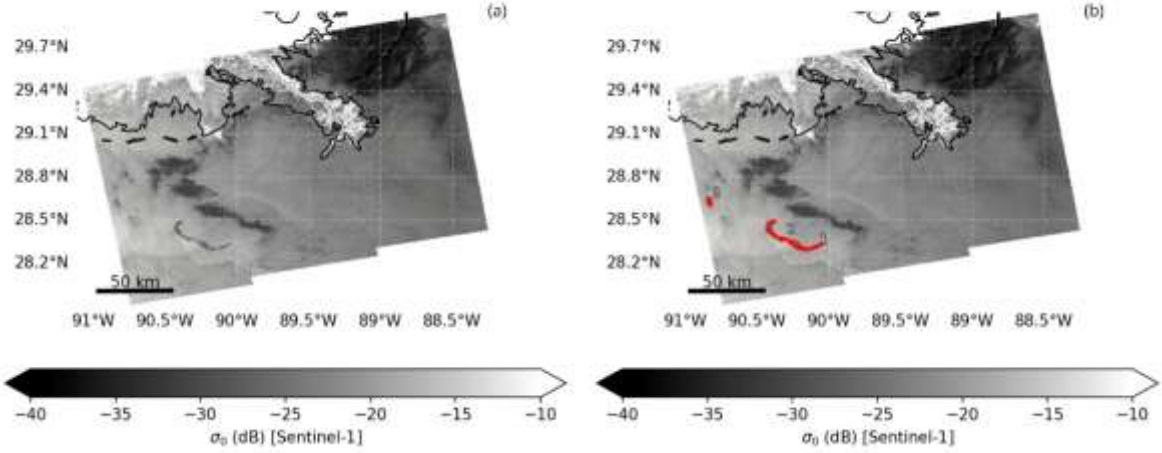
- Input title: `S1A_IW_SLC__1SDV_20210805T000201_20210805T000228_039087_049CB9_D205`
- Input path: `/host/mnt/camobi_process/rioss_outputs/prod/data/76314c45-14f8-578c-8cda-4b47a6f908ca/preproc_sar/76314c45-14f8-578c-8cda-4b47a6f908ca.nc`

Source: SipamMar.

4.3.1 Automated detection

The analyzed SAR image was processed by the SipamMAR system, and the signaled alert was based on a RESNET-50 neural network, with pixel probability indices higher than those pre-established by the warning system. Figure 8 shows, on the left, the original SAR image and, on the right, the result of the semantic segmentation performed by the model, with the regions identified as oil highlighted in red. The analysis was conducted without human intervention, reinforcing the system's autonomy under real operating conditions.

Figure 8 - Imagens SAR D205. (a) Imagem SAR sem detecções; (b) Imagem SAR com as detecções do sistema, marcadas em vermelho



Source: SipamMar.

Figure 9 summarizes the results of oil spill segmentation in the ocean performed by the ResNet-50 convolutional neural network. Three identified polygons with different areas, geographic locations, and detection probabilities are observed. The first polygon, located at approximately 28.3185° longitude and -90.0854° latitude, has an area of 14.18 km², with a detection probability of 58% and a maximum probability of 85%. The second polygon is the largest, with 90.69 km², but has a lower probability (49%), although its estimated maximum is 86%. The third polygon, with only 9.56 km², has the lowest overall (41%) and maximum (80%) probabilities. These results suggest that, despite the consistency in identifying potentially contaminated regions, there is variability in both the spatial extent and the confidence attributed by the model to each detection.

The difference between the average and maximum probability can also indicate internal spatial heterogeneity within the segmented polygons. This pattern is consistent with the diffuse nature of oil slicks observed by remote sensing sensors, as well as with the classifier's limitations in handling transition areas and reduced spectral contrast. The presence of quicklook links facilitates visual verification and qualitative validation of these detections, reinforcing the integration between automated methods and human inspection in the environmental monitoring process.

Figure 9 – Metadata representing the output of the detection model with probability indices, estimated area, and geographic positioning

	Latitude	Longitude	Area (km²)	Probability	Highest Probability	Quicklook
1	-90.0854	28.3185	14.184	58%	85%	link
2	-90.3135	28.3824	90.689	49%	86%	link
3	-90.8336	28.6324	9.555	41%	80%	link

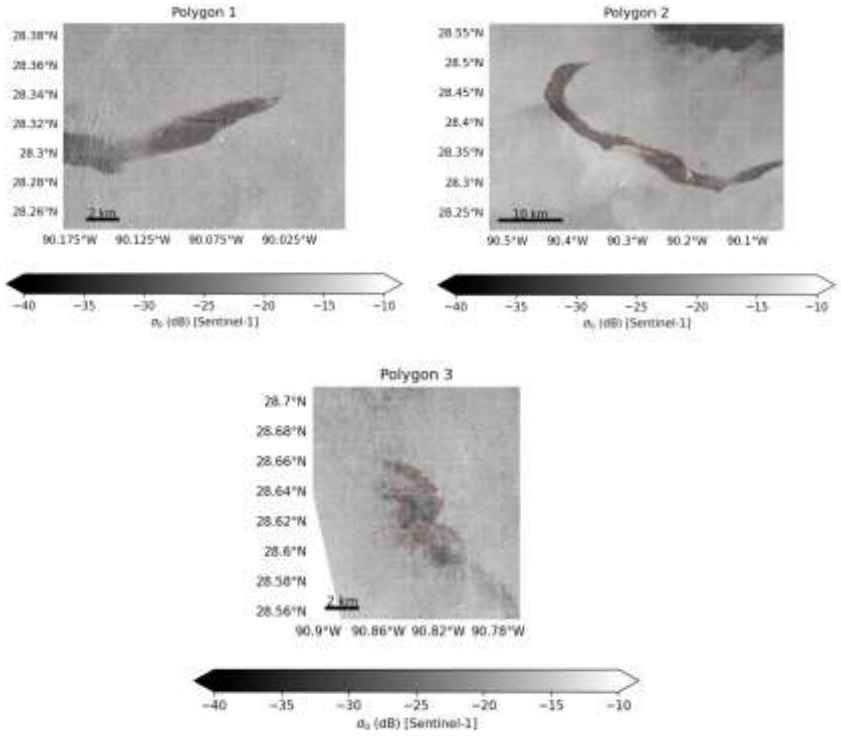
Source: SipamMar.

Figure 10 shows three automatic oil spill detection polygons processed in this case study by the SipamMar system. Each image shows the backscatter signature in decibels (σ_0), with the outlines of the segmented areas marked in red. Polygon 1 (Figure 1) displays a well-defined spill with an elongated structure, centered between 28.26°N and 28.38°N and with a sharp contrast in the σ_0 signature, reaching values below -30 dB, consistent with the suppression of scattering caused by oil films.

Polygon 2 (Figure 2), the largest in area (90,689 km²), presents a curved and extensive feature, with a more heterogeneous spatial distribution pattern and inserted in a hazy background field, which may indicate the presence of atmospheric interference or variations in surface roughness. Polygon 3 (Figure 3) is the smallest of the three, but it reveals a more fragmented and diffuse feature, suggesting oil dispersion or the presence of multiple point sources.

The coherence between the neural network (ResNet-50) contours and the low σ_0 areas reinforces the algorithm's effectiveness for the automatic detection of anomalies consistent with oil spills at sea, even in different morphological and spectral contexts. The visual interpretation, facilitated by the reflectivity scale and distance bars, corroborates the model's robustness in identifying potentially polluting events in oceanic environments.

Figure 10 - Excerpts of the oil slicks, from image D205, detected by the SipamMar system

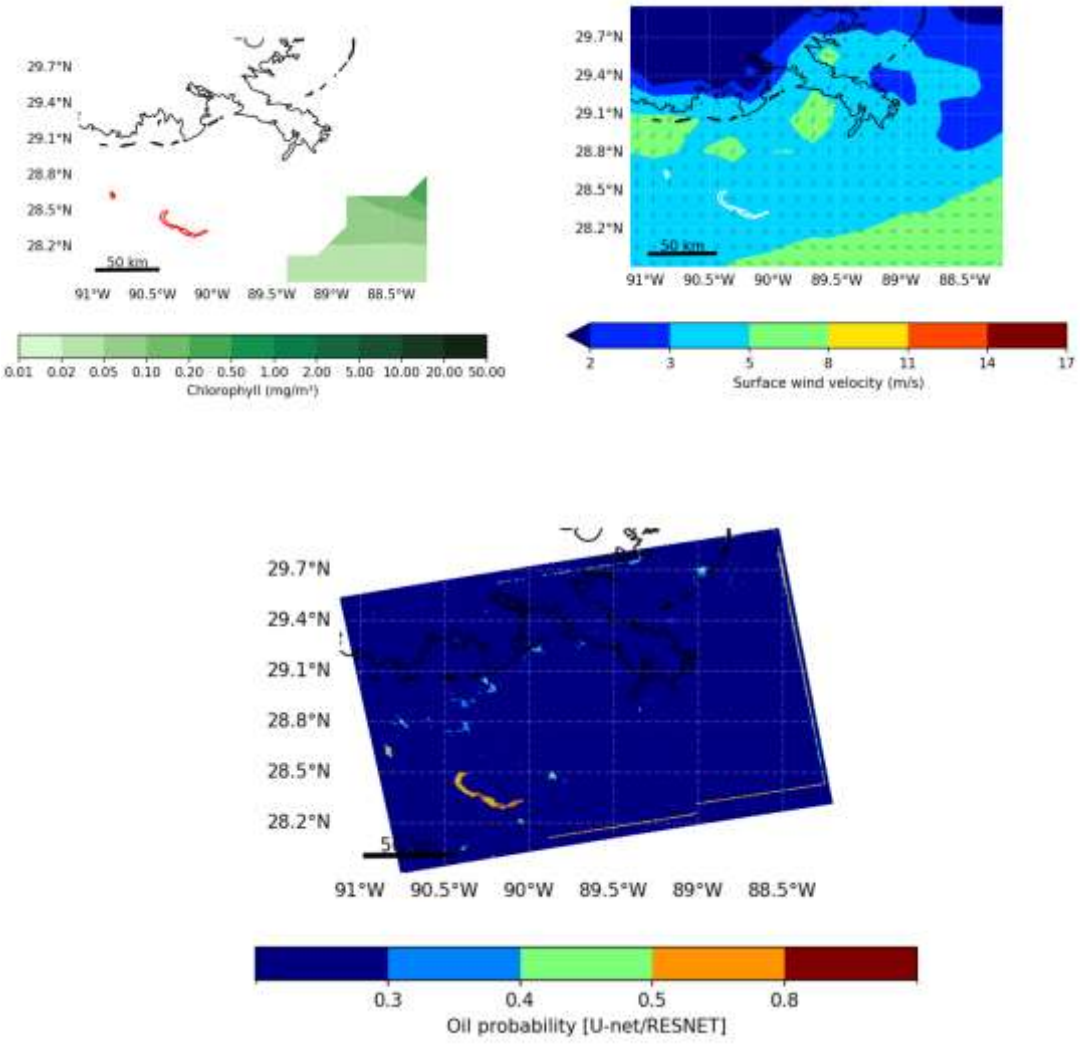


Source: SipamMar.

Figure 11 presents a set of auxiliary data used to support the operator's qualitative analysis in validating an automatic oil spill detection performed by the SipamMar system. The first subfigure shows the chlorophyll-a concentration (mg/m³), where it can be observed that the detected spill area has low levels of phytoplankton biomass, which reduces the possibility of biological fronts or spills of natural origin associated with intense biological activity. The second subfigure shows the surface wind field, evidencing moderate speeds (between 5 and 8 m/s) with a predominant north-south direction, consistent with the alignment and dispersion observed in the suspected feature, reinforcing the hypothesis of passive transport of an oily film.

Finally, the third subfigure shows the oil presence probability map generated by a classifier based on the U-Net architecture combined with ResNet-50, with values greater than 0.8 in the region of the spill, indicating high model confidence in the detection. The combination of these three informative layers—low chlorophyll, wind vector coherence, and high probability—provides a robust basis for confirming the anomaly as a potential oil spill and recent methodological updates applied to artificial intelligence in environmental remote sensing.

Figure 11 – Auxiliary data for predicting oil detection, with maps of surface chlorophyll concentration, wind speed, and the oil probability map associated with the prediction models



Source: SipamMar.

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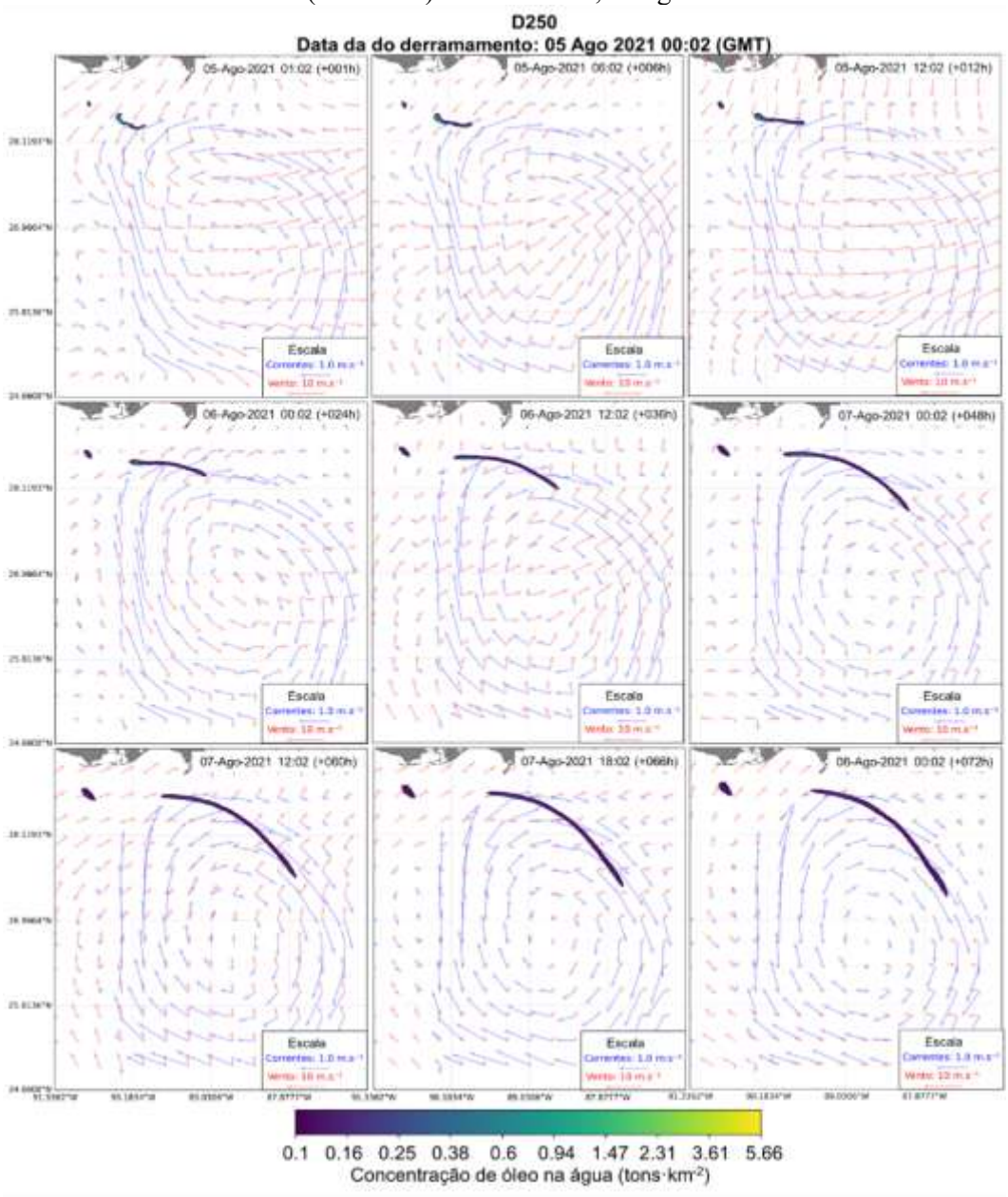
Figure 12 simulates the trajectory and evolution of the oil concentration on the sea surface from a spill event that occurred on August 5, 2021. Each panel represents a time instant, in increments of six hours up to 72 hours after the initial event, revealing the dynamic behavior

of the slick under the combined action of ocean currents (blue vectors) and surface winds (red vectors). The oil slick is represented in shades of purple to yellow, corresponding to the concentration of oil in tons per square kilometer, with the highest values (above 5.66 $t.km^{-2}$) indicated by the lighter shades.

Throughout the simulation, a gradual displacement of the oil slick from west to east-northeast is observed, consistent with the local ocean circulation and the overlying wind field. This pattern highlights the influence of the cyclonic current's rotation in the region and the action of the wind as a secondary driving force, contributing to the transport and deformation of the slick. Numerical predictions show that, in about three days, the slick travels a significant distance, modifying its shape and concentration distribution, which is crucial for assessing environmental impacts and prioritizing responses in sensitive coastal areas or areas of economic activity.

Models like MEDSLIK-II are fundamental tools in the context of responding to environmental emergencies involving oil spills. By integrating remote sensing data with environmental forecasting (wind and current), these models allow for the estimation of the likely trajectory of the oil spill in near real-time, providing technical support for operational decisions, such as the mobilization of containment vessels, the direction of absorption buoys, or the issuance of alerts to coastal communities. Automatic simulation from central points detected by the SipamMar system represents an advance in the automation of monitoring and response, aligning artificial intelligence with predictive modeling in an integrated and efficient approach to environmental disaster management.

Figure 12 – Simulation of oil spill dispersion performed with the MEDSLIK-II model for the event detected on August 5, 2021, at 00:02 GMT (case D250). The panels show the evolution of the surface oil concentration (tons·km^{-2}) over 72 hours, at regular 6-hour intervals



Source: MEDSLIK-II

5 CONCLUSION

The development and implementation of the SipamMAR system represent a significant advancement in the national capacity for environmental monitoring and response to oil spills in Brazilian jurisdictional waters. By integrating SAR remote sensing technologies, deep learning algorithms with convolutional neural networks, and numerical modeling of contaminant

dispersion, the system automates the detection, alert, and forecasting chain, reducing dependence on human actions and optimizing operational efficiency.

The performance of a convolutional neural network in detecting oil slicks in SAR images is intrinsically linked to environmental conditions that influence the backscattering of radar waves on the ocean surface. Factors such as wind speed and direction, for example, are fundamental. Strong winds increase surface roughness, raising overall backscattering and potentially masking the slick, while weak winds can create natural dark patches that can be mistaken for oil, leading to false positives. Furthermore, the concentration of biogenic films, such as chlorophyll, also has the potential to create natural dark patches for SAR sensors and, therefore, the potential to generate false positives.

It was observed that in situations of weak wind, the convolutional network maintained a high detection rate, with average confidence levels higher than the observed average, reflecting the good spectral separability of oil patterns in contrast to calm seas. On the other hand, in conditions with the presence of lookalikes (e.g., algal blooms, thermal fronts, and shear zones), the false positive rate increased by approximately 12–15%, reducing the average confidence level to values higher than those expected by different references cited in the work. This variation indicates that the network is more sensitive to complex surface features than to isolated meteorological conditions.

We also highlight that the consistency with auxiliary data (wind and surface currents) contributed to reducing uncertainty: when associated with oceanographic situations consistent with oil spills (e.g., advection aligned with the prevailing wind), the probability of correct detection was higher. This analysis suggests that future versions of the system could be improved by explicitly integrating environmental variables as additional inputs to the model, increasing its robustness against lookalikes and adverse conditions.

Case studies demonstrate the robustness of the U-Net and ResNet-50 classifiers in segmenting oil spills in SAR images, with consistent performance even in complex environments subject to interference, such as regions with lookalikes or adverse weather conditions. The integration of auxiliary data, such as wind fields, chlorophyll concentration, and detection probabilities, proved essential for reducing false positives and validating the detected anomalies.

This multivariate approach strengthens decision-making and contributes to a faster and more informed response. In turn, predictive modeling with MEDSLIK-II, automatically fed by high-resolution observational and predictive data, allows for the simulation of realistic oil

transport and transformation scenarios, providing fundamental technical support for the actions of environmental agencies, maritime authorities, and port operators.

Despite the progress achieved, it is important to acknowledge some limitations of this study. We emphasize that systematic statistical validation of the automatic detections, based on in situ test events, was not conducted. We believe this restricts the quantification of classifier performance in varied real-world scenarios. To overcome this problem, we have a group of trained operators to verify each warning signal from the system. Another important aspect to consider is the predominance of the use of simulated data or specific case studies, still lacking broad and continuous real-time operational application. This will allow SipamMar to assess the system's robustness against different types of oil and marine biomes.

As future perspectives, we highlight the expansion of the training database with data from multiple sensors, the integration of statistical validation routines comparing automatic detections with field observations, and the testing of the platform in different coastal and oceanic environments. Furthermore, the incorporation of SipamMar into governmental emergency response protocols could enhance its practical impact, expanding support for monitoring and mitigating oil spills in Brazilian jurisdictional waters.

Given the challenges posed by the vastness of the Blue Amazon and the increasing anthropogenic pressure on marine ecosystems, SipamMAR offers an autonomous, scalable, and highly strategic technological alternative. By consolidating the application of artificial intelligence and environmental modeling in the context of ocean surveillance, the system is configured as a state tool for the protection of marine resources, reinforcing national sovereignty, environmental security, and the capacity to respond to large-scale ecological disasters.

The system represents a significant advance in Brazil's capacity to respond to environmental incidents at sea, especially by integrating different data sources, process automation, and spatial visualization to support decision-making. It is expected that, with continued development and the incorporation of new functionalities, such as environmental impact indices and an integrated web interface, the system can be consolidated as a strategic solution for the protection of the Blue Amazon and the country's coastal zones.

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The threat of transnational organized crime to the protection and sustainable future of the Brazilian Amazon

A ameaça do crime organizado transnacional à proteção e ao futuro sustentável da Amazônia brasileira

La amenaza del crimen organizado transnacional a la protección y al futuro sostenible de la Amazonía Brasileña

La menace du crime organisé transnational sur la protection et l'avenir durable de l'Amazonie Brésilienne

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Abstract
This article analyzes the impacts of transnational organized crime (TOC) on the protection and sustainable future of the Brazilian Amazon. It argues that the presence of criminal organizations in the region has intensified illegal deforestation, facilitated by logistical networks, institutional corruption, and violence against communities and environmental agents. By integrating geospatial data from PRODES/INPE with records of criminal organizations' activities, the study conducts a quantitative and qualitative analysis of municipalities within the Legal Amazon. The findings reveal a significant territorial correlation between the presence of criminal organizations and accumulated deforestation levels. It concludes that TOC poses a direct threat to national sovereignty and the environmental integrity of the region, demanding integrated responses through security, defense, and sustainable development policies.

Keywords: Brazilian Amazon; transnational organized crime; deforestation.

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Resumo
Este artigo analisa os impactos do crime organizado transnacional (COT) sobre a proteção e o futuro sustentável da Amazônia brasileira. Argumenta-se que a presença de facções criminosas na região tem ampliado o desmatamento ilegal, facilitado por redes logísticas, corrupção institucional e violência contra comunidades e agentes de fiscalização. A partir da integração de dados geoespaciais do PRODES/INPE e registros da atuação de organizações criminosas, realiza-se uma análise quantitativa e qualitativa dos municípios da Amazônia Legal. Os resultados indicam uma correlação territorial relevante entre a presença de facções e os níveis de desmatamento acumulado. Conclui-se que o COT representa uma ameaça direta à soberania nacional e à integridade ambiental da região, exigindo respostas articuladas entre políticas de segurança, defesa e desenvolvimento sustentável.

Palavras-chave: Amazônia brasileira; crime organizado transnacional; desmatamento.

Resumen
Este artículo analiza los impactos del crimen organizado transnacional (COT) sobre la protección y el futuro sostenible de la Amazonía brasileña. Se sostiene que la presencia de facciones criminales en la región ha intensificado la deforestación ilegal, facilitada por redes logísticas, corrupción institucional y violencia contra comunidades locales y agentes de fiscalización. A partir de la integración de datos geoespaciales del PRODES/INPE y de registros sobre la actuación de organizaciones criminales, se realiza un análisis cuantitativo y cualitativo de los municipios de la Amazonía Legal. Los resultados muestran una correlación territorial significativa entre la presencia de facciones y los niveles de deforestación acumulada. Se concluye que el COT representa una amenaza directa a la soberanía nacional y a la integridad ambiental de la región, lo que exige respuestas articuladas entre las políticas de seguridad, defensa y desarrollo sostenible.

Palabras clave: Amazonía brasileña; crimen organizado transnacional; deforestación.

Résumé
Cet article analyse les impacts du crime organisé transnational (COT) sur la protection et l'avenir durable de l'Amazonie brésilienne. Il soutient que la présence de factions criminelles dans la région a intensifié la déforestation illégale, facilitée par des réseaux logistiques, la corruption institutionnelle et la violence dirigée contre les communautés locales et les agents de contrôle. En intégrant des données géospatiales du PRODES/INPE et des registres relatifs aux activités des organisations criminelles, l'étude réalise une analyse quantitative et qualitative des municipalités de l'Amazonie légale. Les résultats révèlent une corrélation territoriale significative entre la présence de factions et les niveaux de déforestation accumulée. L'article conclut que le COT constitue une menace directe à la souveraineté nationale et à l'intégrité environnementale de la région, exigeant des réponses coordonnées entre les politiques de sécurité, de défense et de développement durable.

Mots-clés : Amazonie brésilienne ; crime organisé transnational ; déforestation.

1 INTRODUCTION

Organized crime has increased its presence in the Amazon over time, particularly in the second decade of the 21st century (Couto, 2023, p.47). In 2023, 22 criminal groups were present in 178 municipalities (Fórum Brasileiro de Segurança Pública, 2024, p.71). In 2024, despite having decreased to 19, these criminal organizations were established in 260 municipalities (Brazilian Forum on Public Safety, 2024, p.71), out of the 773 existing in the Legal Amazon (Brazilian Institute of Geography and Statistics, IBGE, 2025), denoting activity in about 34% of the Amazon region's territory.

Organized crime is not limited to the Brazilian Amazon. On the contrary, its activities extend throughout the Pan-Amazon region (Lima, 2023), reaching countries such as Bolivia, Colombia, Ecuador, Guyana, French Guiana, Peru, Suriname, and Venezuela. In Peru, for example, studies show that organized crime has caused about 20% of the forest's deforestation due to the cultivation of coca leaves. According to the United Nations Office on Drugs and Crime (UNODC), drugs produced in Peru, as well as those from Colombia and Bolivia, enter Brazilian territory to reach domestic users and to be exported to Europe or Africa (UNODC, 2023, pp. 70 and 81). In addition, other illegal activities carried out by transnational organized crime (TOC), such as mining and illegal exploitation of forest resources (UNODC-DEVIDA, 2024), have threatened the forest and biodiversity of the region.

The Global Initiative Against Transnational Organized Crime (2023, p.5) contends that shipments of cocaine, precious minerals, and timber – moving along Amazonian rivers and clandestine airstrips – fuel the growing global demand and contributes directly to deforestation. The organization also highlights that transnational organized crime poses an existential threat to the most biodiverse region on the planet.

The Brazilian Forum on Public Security (2023, p.11) emphasizes that it is impossible to design policies and strategies to preserve the Amazon rainforest without addressing the threats that crime represents to the Amazon region. Given the seriousness of the issue, the leaders of the States Parties to the Amazon Cooperation Treaty (ACT), participating in the 2023 Amazon Summit, agreed to convene a Meeting of Ministers of Public Security to assess criminal dynamics and transnational organized crime in the Amazon, as well as to promote the information-sharing and strengthen police cooperation against illicit activities and environmental crimes in the area (Brasil, 2023).

Given this complex scenario, the guiding question for this article was: how does transnational organized crime impact illegal deforestation rates, with potential negative consequences for the protection and sustainable future of the Brazilian Amazon? The core objective is to identify the impacts that the threat of transnational organized crime poses to the Amazon in terms of illegal deforestation. The relevance of this investigation lies in the centrality of the Amazon to global climate dynamics – dependent on the maintenance of forest cover – and in the multifaceted threats that TOC represents to national security and environmental integrity.

The article is organized as follows: the introduction contextualizes the problem of transnational organized crime in the Amazon and sets out the research objective. The second section presents a qualitative analysis of the phenomenon, examining organized crime and its relationship with illegal deforestation. The third section addresses the quantitative analysis, based on the available statistical data, assessing the connection between TOC and illegal deforestation. The fourth section discusses the findings of the two previous sections. Finally, the conclusion highlights the implications for public policy formulation and suggests avenues for future research.

2 METHODOLOGY AND MATERIALS

For this article, an applied quali-quantitative research methodology was adopted, structured along two complementary methodological axes.

The first axis consisted of qualitative, bibliographic research aimed at identifying the connections between criminal organizations and illegal deforestation, as well as other illicit economic activities that contribute to it – such as money laundering, unlawful acquisition of land for agricultural purposes, and illegal mining. This bibliographic review drew on scientific articles available on digital platforms such as Google Scholar and EBSCOhost. Sources were selected based on thematic alignment, relevance to the research question, and their quality and currency.

The second axis comprised: (1) a comparative statistical analysis of deforestation between 2000 and 2023 involving municipalities in the Legal Amazon[1] – with and without

[1]Legal Amazon in data

the presence of criminal organizations – which included the production of graphical outputs; (2) application of the Welch's t-test[2] to determine whether the differences between the samples are statistically significant; (3) a multivariate logistic regression with "deforestation" as the dependent variable – with the purpose of assessing the probability of influence exerted by criminal organizations on deforestation—and the following independent variables[3]: a) extent of deforested areas; b) presence of TOC organizations; c) size of arable land in the Legal Amazon; d) number of cattle per municipality; e) municipal area; f) presence of conservation units within municipalities; g) presence of Indigenous lands within municipalities; h) length of highways within the states (given their probable impact on illegal logistics flows); i) Federal Police operations in the area; and j) deforestation rates; (4) the Mann–Whitney U test, a non-parametric statistical test used to verify whether the difference between municipalities with and without criminal organizations is significant; and (5) finally, using PRODES/INPE deforestation rate data and applying ARIMA (autoregressive integrated moving average) time-series modeling to forecast possible future values, the study sought to outline the prospective deforestation scenario.

The databases used were: (1) PRODES Deforestation, from INPE (2000–2023); (2) TerraBrasilis – PRODES (Deforestation), 2000–2023; (3) Legal Amazon, from IBGE (2025); (4) Brazilian Forum on Public Security (2024), for identifying the presence of criminal organizations in the municipalities and police operations carried out in the Amazon against crimes associated with deforestation; (5) the IBGE Automatic Recovery System (2025) for agricultural and livestock data; (6) IBGE (2025) for data on the municipal road network, which facilitates the illegal transport logistics of timber; (7) FUNAI (2025) for identifying Indigenous lands within municipalities; and (8) the Ministry of the Environment (2025) for identifying conservation units present in the municipalities.

[2] Welch's t-test is a variation of the Student's t-test used to compare the means of two independent groups when their variances and/or sample sizes differ. It is the standard test when the assumption of equal variances is not plausible. Since the p-value was lower than 0.05, the hypothesis that deforestation in areas where TOC occurs by chance is rejected.

[3] The independent variables used in the multivariate logistic regression were defined based on their relevance and their hypothesized correlation with deforestation in areas with or without the presence of TOC, namely: (1) the extent of deforested areas, the presence of factions, the size of arable land, the number of cattle per municipality, the municipality's area, the presence of conservation units, the presence of Indigenous lands, the length of highways, and the number of Federal Police operations in the municipality. It is worth noting that the selected variables yielded a statistically predictive model.

3 RESULTS

3.1. QUALITATIVE ANALYSIS

The purpose of this section is to conduct a qualitative analysis of the relationship between criminal organizations and deforestation in the Legal Amazon.

According to Margulis (2003, p. 11), in the 1970s and 1980s, deforestation in the Amazon was primarily driven by the economic occupation of the territory, induced by government incentives and policies. In the 1990s, the increase in deforestation was caused by private-sector activities, particularly cattle ranching. At the time, Margulis warned that the financial viability of medium- and large-scale cattle ranchers functioned as the engine of deforestation (p. 14), while agricultural activity did not compete with ranching because it faced geo-ecological constraints, such as the region's high rainfall (p. 15). In that study, cattle-raising activities accounted for roughly 75% of deforested areas in the Amazon (p. 15). It is worth noting that until 1970, agricultural censuses indicated that only about 3% of Amazonian land had been cleared up for agricultural purposes, but by 2003 this share had surpassed 10% (p. 28). By 2020, 2% of all properties in the Amazon and Cerrado were responsible for 62% of all potentially illegal deforestation, and 17% of beef exports from both biomes to the European Union could be linked to illegal deforestation (Rajão *et al*., 2020).

With the expansion of TOC activity in the Amazon beginning in the 2010s, the dynamics of illegal deforestation shifted from being driven solely by economic pressures – combined with weak state oversight – to incorporating the influence of criminal organizations. According to the Igarapé Institute (2024, p. 3), a significant share of deforestation in the Amazon region results from illegal activities sustained by national and transnational criminal networks. The Institute highlights that deforestation is propelled by a set of illicit economic practices, such as land grabbing and cattle ranching with illegal practices in the supply chain, illegal logging, and illegal mining[4] (p. 4). Carneiro and Rosas (2025, p. 6) note that failures in land registration systems in the Amazon facilitate land grabbing, and shortcomings or gaps in environmental legislation encourage illegal timber exports and illegal gold mining, creating numerous opportunities for criminal organizations.

[4] According to the Global Initiative (2023, p. XXX), illegal gold extraction in the Amazon increased by 94% between 2016 and 2021, making it one of the main drivers of deforestation in the region.

According to Brombacher and Santos (2023, p. 15), the direct impact of drug cultivation on deforestation is limited, but there is evidence that the "drug economy"[5] drives the expansion of the agricultural frontier, as well as cattle ranching and mining activities that have the potential to increase deforestation in the Amazon. UNODC refers to this connection and overlap of illegal activities that affect the environment as "criminal convergence," which encompasses corruption, money laundering, fraud, extortion, violence, and other illicit activities (UNODC, 2023, p. 91). This concept is consistent with what Carneiro and Rosas (2025, p. 7) describe as a form of articulation of multiple illicit activities developed through networks of cooperation and facilitation involving drug trafficking, illegal logging, illegal mining, land grabbing, and money laundering.

In terms of transnational criminal organizations operating in the Amazon, the most prominent are *Comando Vermelho* (CV) and *Primeiro Comando da Capital* (PCC) (Cardoso, 2020, p. 15). Within the broader conception of criminal networks, in addition to PCC and CV, the following criminal organizations (ORCRIM) also operate in the Amazon and maintain, in various ways, connections with those two major groups: *Bonde dos 13, Bonde dos 40*, *União Criminosa do Amapá*, *Família Terror do Amapá, Os Crias, Piratas do Solimões, Família do Norte, Primeiro Comando Panda, Trem de Arágua, Trem da Guayana, Sindicato*, among others. Moreover, dissident elements of the FARC or members of the Shining Path maintain ties with Brazilian criminal organizations (Parente, 2020, p. 22–23).

These criminal groups are motivated by profit and power, employ business-style planning practices, and co-opt state agents to facilitate illegal activities (Mingardi, 2007, p. 56). Environmental crimes, for instance, generate between US$110 and US$281 billion annually (Igarapé Institute, 2024, p. 4). As a result, criminal organizations seek to launder proceeds from the drug market by reinvesting their profits in the legal and illegal acquisition of land (including land grabbing), deforestation for pasture creation, and other agricultural activities, thereby producing narco-deforestation[6] (UNODC, 2023, p. 67).

Criminal organizations possess multiple capabilities for committing illicit activities, such as: (1) territorial control for establishing drug-trafficking routes (Funari, 2024, p. 5); (2)

[5] The drug economy encompasses production, distribution, and consumption, as well as the profits generated, the social and financial impacts, and the social costs it produces.

[6] According to the World Drug Report, narco-deforestation consists of deforestation carried out for real estate speculation or to serve the agribusiness sector, which in fact conceals the laundering of drug trafficking proceeds (UNODC, 2023, p. 61).

construction of illegal airstrips and clandestine roads (Couto, 2000, pp. 10 and 12); (3) access to firearms (Brazilian Forum on Public Security, 2023, p. 10); (4) recruitment of new members, including Indigenous individuals (Lima, Ambrósio and Farias, 2025, p. 3); (5) generating profits through drug and arms trafficking, deforestation, land grabbing, and illegal mining (Guaraldo, 2025); (6) money laundering from illegal mining and agribusiness activities (Júnior and Costa, 2023, pp. 153–155); (7) establishing financial networks to move and conceal illicit transactions (Muller, 2024, p. 21); (8) corruption of public officials to facilitate operations and ensure impunity (Igarapé Institute, 2024, p. 25); (9) control over local communities (Costa, Almeida and Oliveira, 2024, p. 310); (10) intimidation of locals, environmental activists, and authorities (Araújo, 2024, p. 29); (11) expansion into new municipalities (Couto, 2023, p. 63); and (12) formation of strategic alliances (Couto and Netto, 2025, p. 38).

According to Waisbich *et al.* (2022, p. 8), illegal deforestation results from four illicit activities: (1) land grabbing; (2) illegal logging; (3) illegal mining; and (4) agriculture and cattle ranching linked to environmental illegality. To substantiate this assessment, data from 369 Federal Police operations (p. 11) conducted between 2016 and 2021 were analyzed, which revealed the following:

Table 1 – Relationship between deforestation and other illicit economic activities

		Relationship with the main target				
Number of Operations	Main Target	Illegal logging	Land grabbing of public lands	Ilegal mining	Agribusiness with illegal environmental practices	Ilegal deforestattion
100	Ilegal deforestattion	32%	66%	21%	13%	-
53	Land grabbing of public lands	11%	-		7%	35%
151	Illegal logging	-	32%	3%	27%	49%
170	Ilegal mining	3%	7%	-	13%	21%
15	Agribusiness with illegal environmental practices	3%	19%	1%	-	13%

Source: Author's elaboration, based on data from Waisbich *et al.* (2022, p. 11).

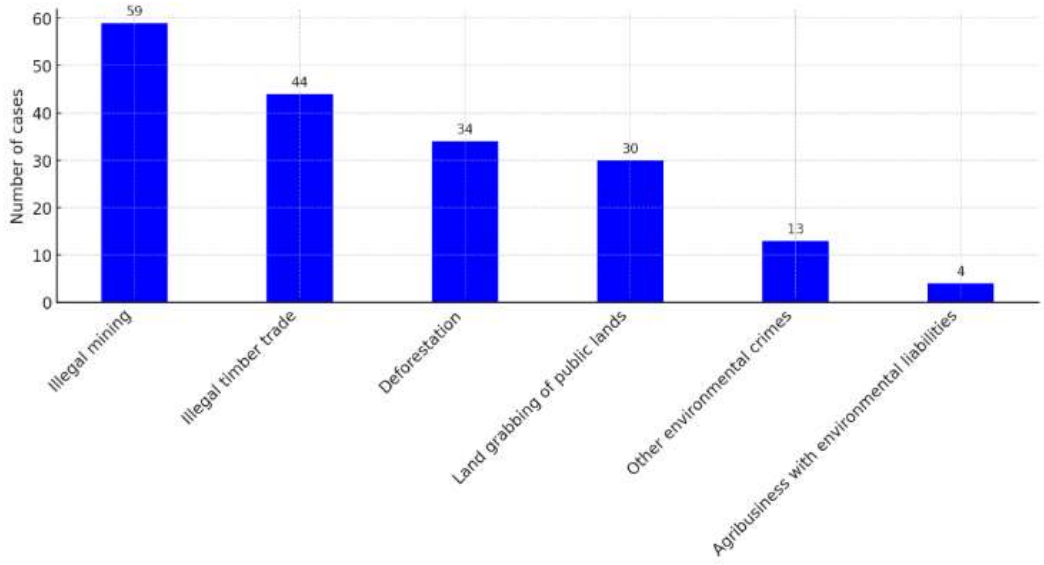
The data show that deforestation almost never occurs in isolation; there is a significant connection between deforestation, land grabbing on public lands, and illegal logging. By

contrast, the relationship between illegal deforestation and mining or agricultural activities that harm the environment appears to be less pronounced. Even so, according to the report *Contemporary Issues on Drugs* (UNODC, 2023, p. 63), there is evidence that drug traffickers finance logistical support for certain illegal mining operations, expanding their activities into illegal logging.

According to the Brazilian Forum on Public Security, Pará has been the state with the highest number of recorded cases of illegal deforestation (2023, p. 99). The organization also highlights the main drivers of deforestation across Amazonian states, as follows: (1) logging and cattle ranching intensify deforestation in northern Mato Grosso, Rondônia, and Acre; (2) logging and illegal mining affect southern Amazonas and the state of Roraima; (3) logging, agriculture, and cattle ranching catalyze deforestation in Mato Grosso and Mato Grosso do Sul; (4) logging, illegal mining, agriculture, and cattle ranching impact Pará; and (5) agriculture and illegal mining accelerate deforestation in Maranhão (2023, p. 103).

According to the Igarapé Institute, between 2016 and 2022, the Federal Police (PF) recorded the following environmental crimes:

Graphic 1 – Cases of environmental crimes recorded by the Federal Police, 2016–2022

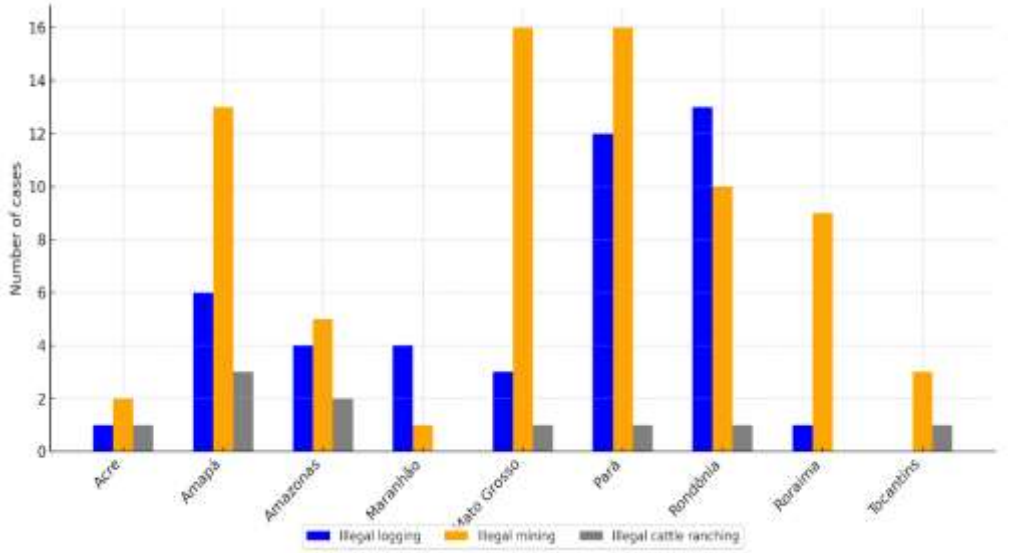


Source: Author's elaboration, based on data from the Igarapé Institute (2024).

It is evident that there is a portfolio of environmental crimes that are interconnected, such as deforestation and the illegal timber trade, or deforestation carried out for the creation

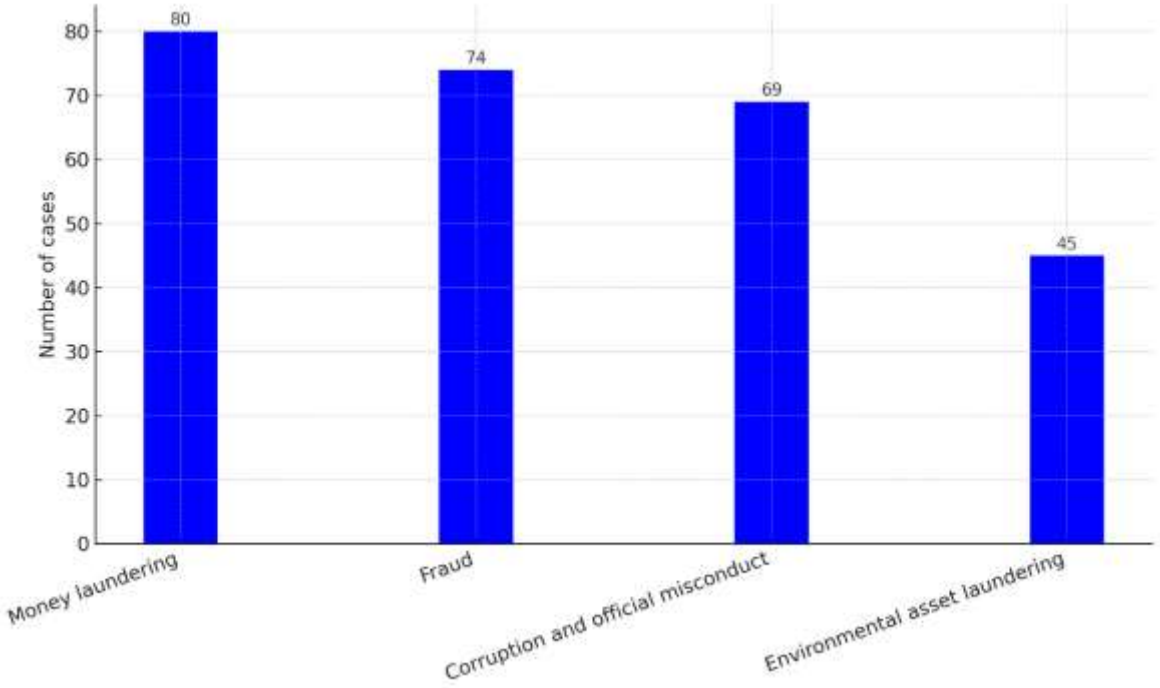
of pastures. The crimes mapped by the Federal Police were geographically distributed as follows:

Graphic 2 – Number of environmental crimes recorded by the Federal Police, 2016–2022



Source: Author's elaboration, based on data from the Igarapé Institute (2024).

Graphic 3 – Cases mapped by the Federal Police of economic offenses linked to environmental crimes between 2016 e 2022



Source: Author's elaboration, based on data from the Igarapé Institute (2024).

The records of environmental crimes and related economic offenses demonstrate criminal convergence and their connection to the illegal deforestation carried out by criminal organizations.

3.2 QUANTITATIVE ANALYSIS

This section presents the quantitative assessment of the relationship between organized crime and illegal deforestation in the Brazilian Amazon, drawing primarily on data from the region's monitoring systems: PRODES/INPE (2000–2023) and TerraBrasilis (2000–2023).

Acre stands out with 100% of its municipalities reporting the presence of criminal organizations (ORCRIM), indicating broad territorial dominance—most notably by *Comando Vermelho* (CV), which operates in 18 municipalities. Roraima follows, with criminal organizations present in 93% of its municipalities. Pará is the state with the highest number of criminal groups, followed by Maranhão. In Amazonas, 21 of 62 municipalities report the presence of organizations. Maranhão registers 48 municipalities with ORCRIM (48 out of 181), representing approximately 27% of its territory. CV also dominates 23 municipalities (out of 142) in Mato Grosso, a state in which agricultural and cattle ranching activities predominate. In Pará, 73 municipalities host criminal organizations, corresponding to roughly 51% of its 144 municipalities. The lowest levels of criminal organization presence are found in Tocantins and Amapá.

It is observed that *Comando Vermelho* holds dominance in approximately 49% of the municipalities where criminal organizations are present, with particular prominence in Acre (AC), Amazonas (AM), Maranhão (MA), and Pará (PA).

Primeiro Comando da Capital (PCC) operates in 11% of the municipalities with criminal organizations, especially in Rondônia (RO) and Roraima (RR).

There are 44 records of the coexistence of CV and PCC within the same municipalities, a situation that may give rise to disputes between the organizations or to some form of arrangement enabling them to jointly carry out their illegal activities profitably.

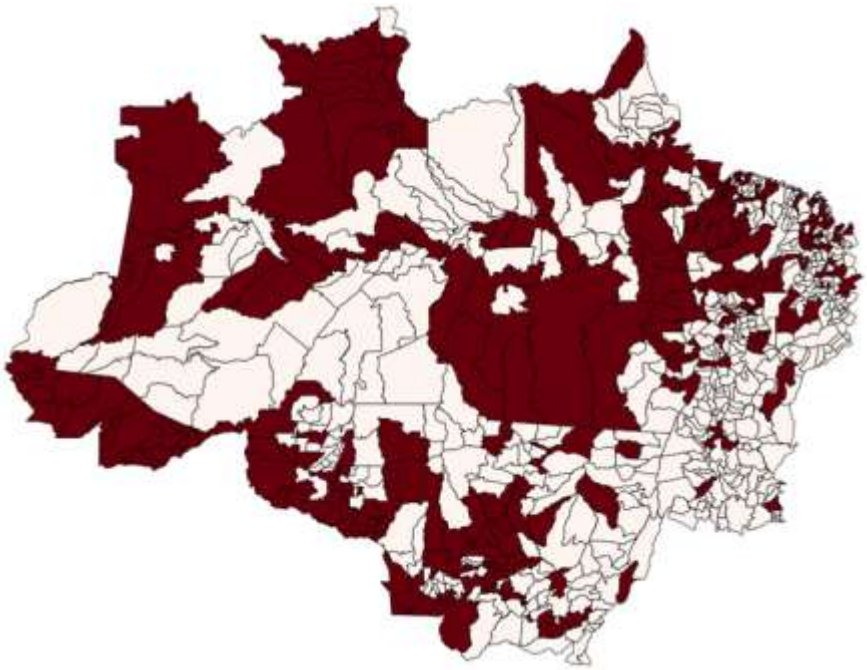
Table 2 – Presence of Organized Criminal Groups in the Amazon Region

STATE	NUMBER OF MUNICIPALITIES	MUNICÍPIOS COM FACÇÕES CRIMINOSAS	PRESENCE OF CV	PRESENCE OF PCC	PRESENCE OF TWO OR MORE CRIMINAL ORGANIZATIONS OR DOMINANCE OTHER THAN CV OR PCC
AC	22	22	18	-	4
AM	62	21	10	-	11
AP	16	5		1	4
MA	181	48	11	3	34
MT	142	42	23	1	18
PA	144	73	60	3	10
RO	52	26	3	13	10
RR	15	14	1	6	7
TO	139	9	1	2	6

Source: Author's elaboration, based on data from the Brazilian Forum on Public Security (2024).

Geographically, the distribution of municipalities in the Legal Amazon with the presence of criminal organizations is as follows:

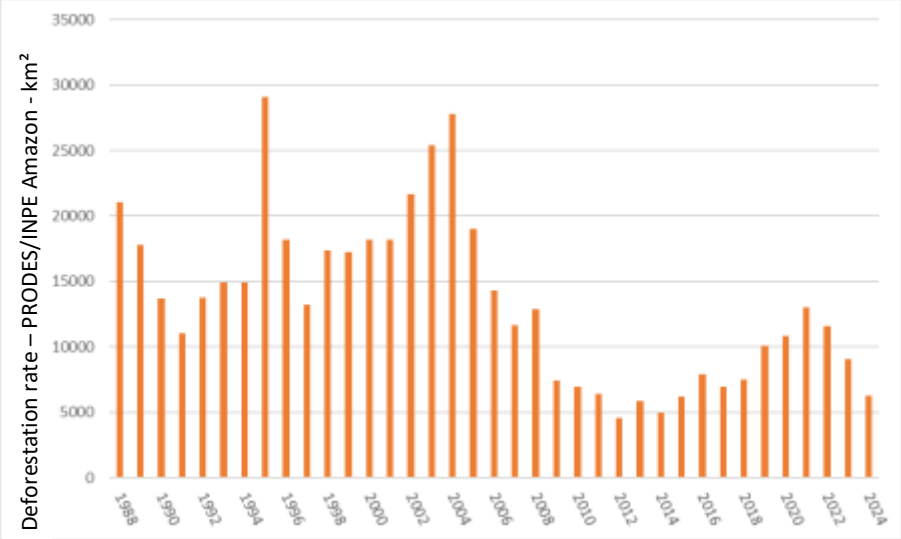
Figure 1 – Municipalities in the Amazon with the presence of criminal organizations



Source: Author's elaboration, based on data from the Brazilian Forum on Public Security (2024).

According to PRODES/INPE data (2000–2023), the deforestation rate in the Amazon over time has evolved as shown in the graph below:

Graphic 4 – Deforestation rate – PRODES/INPE Amazon - km²



Source: Author's elaboration based on PRODES data (2025).

Of the 260 municipalities with the presence of criminal organizations (out of the 773 that make up the Legal Amazon), deforestation data are available for 233. For the 513 municipalities without the presence of criminal organizations, data were identified for 323 cities. The absence of data for 190 municipalities may be due to the lack of continuous deforestation patches larger than 6.25 hectares between 2000 and 2023.

When comparing deforestation across municipalities in the Legal Amazon, it was found that the average deforestation rate in municipalities with the presence of criminal organizations is approximately 1.39 times higher than in municipalities without criminal groups. When assessing the median, municipalities with criminal organizations show values 1.26 times higher than the others.

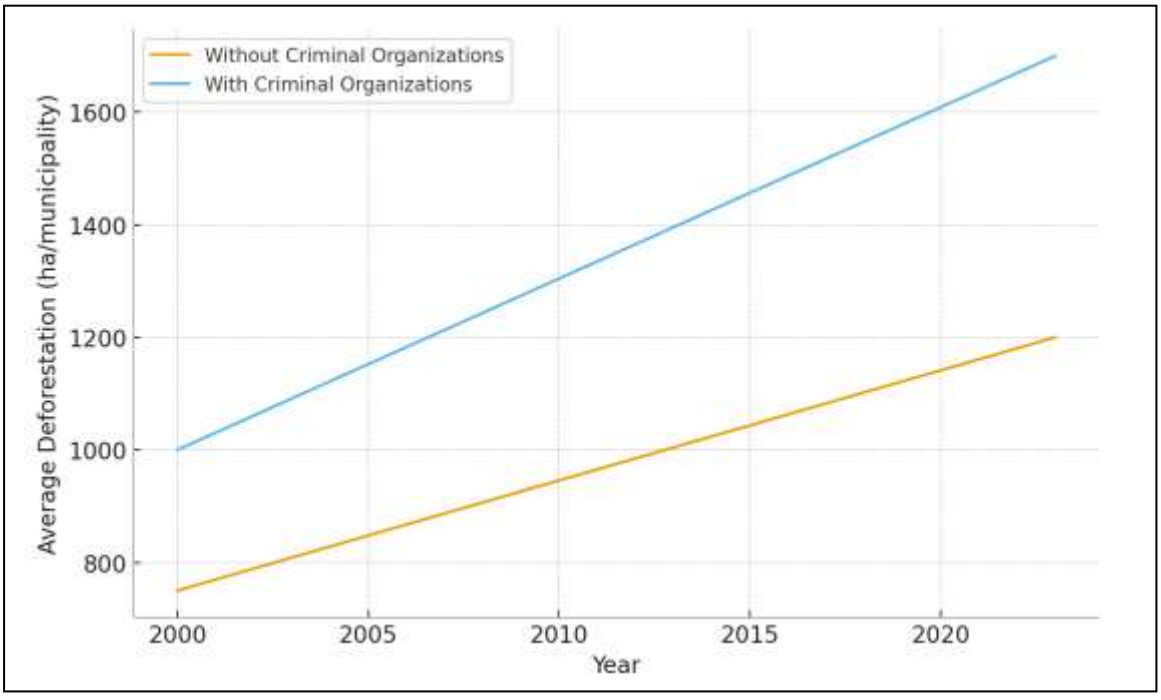
Table 3 – Comparative Descriptive Statistics – Deforestation in the Legal Amazon[7]

INDICATOR	MUNICIPALITIES WITHOUT CRIMINAL ORGANIZATIONS	MUNICIPALITIES WITH CRIMINAL ORGANIZATIONS
N	323	233
Mean annual deforestation (ha/year)	1035.48	1434.27
Median (ha/year)	707.52	894.11
Standard Deviation	1134.33	1817.43

Source: Author's elaboration based on data from PRODES/INPE (2000–2023) and the Brazilian Forum for Public Security (2024).

In order to verify whether the difference in mean deforestation between municipalities with and without criminal organizations is statistically significant, Welch's **t-test** was applied. The test yielded a value of 2.95 and a **p-value of 0.0033 (below 0.05)**, **demonstrating statistical significance**. This result confirms that the presence of criminal organizations contributes to increased deforestation.

Graphic 5 – Average municipal deforestation (2000–2023): municipalities with and without the presence of criminal organizations



Source: Author's elaboration based on PRODES/INPE data (2000–2023) and data from the Brazilian Forum on Public Security (2024).

[7] Values calculated based on the annual average deforestation per municipality for the period 2000–2023, after merging the deforestation data from PRODES (2000–2023) with the criminal group data from the Brazilian Forum on Public Security (2024).

In order to assess the impact of criminal organizations (ORCRIM) on the likelihood of deforestation, a multivariate cross-sectional logistic regression was conducted for the period 2000–2023. The dependent variable was defined as *deforestation* = 1 when the municipality exhibited a total deforested area greater than zero (PRODES/INPE 2025), and *deforestation* = 0 otherwise. The independent variables included: (1) municipal land area (log of area); (2) presence of criminal organizations; (3) extent of arable land within the municipality (log of planted area); (4) number of cattle per municipality (log and density per km²); (5) presence of protected areas (dummy); (6) presence of Indigenous lands (dummy); and (7) extent of the municipal road network (log and density per km²).

The **odds ratio**[8] for the presence of criminal organizations was approximately 2.78 (95% CI: 1.55–4.98; $p < 0.001$)[9]. This means that, holding all other independent variables constant, municipalities with the presence of criminal organizations are about 2.8 times more likely to report some level of deforestation during the period analyzed. In absolute terms, the average marginal effect corresponds to an increase of approximately 15 percentage points in the probability of occurrence.

The estimated impact of organized crime (TOC) on deforestation can be calculated as follows:

$$\text{Relative TOC Impact (\%)} = 100 \times \frac{\text{Deforestation growth with criminal organizations} - \text{Deforestation growth without criminal organizations}}{\text{Deforestation growth without criminal organizations}}$$

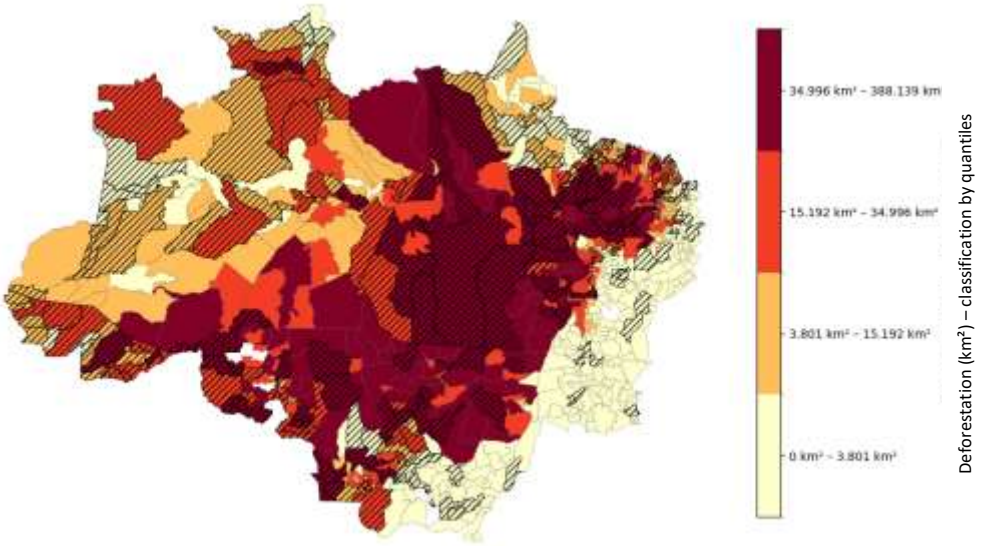
$$\text{Relative TOC Impact } (\%) = \frac{21.80 - 17.49}{17.49} \text{X } 100$$

The estimated relative impact of TOC on deforestation is approximately 24.62%. In the map below, it is possible to observe the overlap between deforestation and the presence of criminal organizations (ORCRIM), allowing the identification of the areas most likely to be affected by organized crime.

[8] The odds ratio (OR) is used to compare two scenarios. When OR > 1, there is an increased likelihood of the event occurring.

[9] 95% confidence interval (CI). The presence of criminal organizations increases the likelihood of deforestation by at least 55% and may reach nearly fivefold, with the most likely estimate around 2.8 times. A *p*-value < 0.001 indicates the statistical significance of the study.

Figure 2– Deforestation by municipality and presence of criminal organizations (black hatching)



Source: Author's elaboration, with data from the Brazilian Public Security Forum (2024) and TerraBrasilis (2000–2023).

In the statistical models used to assess the intensity of organized crime's influence (restricted to municipalities that already exhibit deforestation), the effect of criminal organizations was small and statistically insignificant; no evidence emerged of a convincing causal increase attributable to their presence. This outcome arises primarily from the lack of concrete information on when organized crime began operating in each municipality, as well as the absence of objective data directly linking deforestation to criminal organizations (ORCRIM).

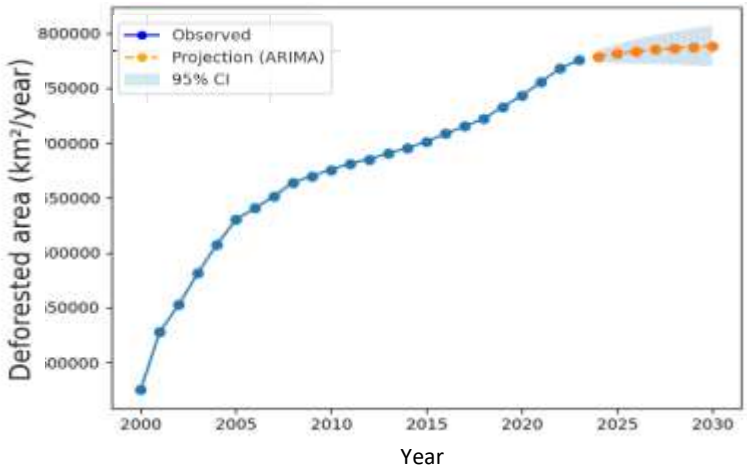
In summary, the presence of criminal organizations increases the likelihood that a municipality will fall into the group that engages in deforestation; however, there is still no evidence that they are the direct cause of the increase in deforestation.

It is important to note the difficulty in measuring data due to the lack of integration of information across the various agencies that deal directly or indirectly with intelligence related to TOC. A significant share of deforestation incidents never comes to the attention of state police forces—either because other institutions become aware of them but do not report them, or because these incidents are not detected by any institution (Forum Brasileiro de Segurança Pública, 2023, p. 100).

Using PRODES/INPE deforestation rate data (2000–2023) and applying an ARIMA (autoregressive integrated moving average) model—i.e., a time-series analysis and forecasting

technique—a projected deforestation scenario was identified with the following characteristics: (1) a trend toward reaching 813,838 km² of accumulated deforested area; (2) a lower-bound estimate of 752,689 km²; and (3) an upper-bound estimate of 874,987 km². The figure below illustrates the possible deforestation scenarios for the Legal Amazon.

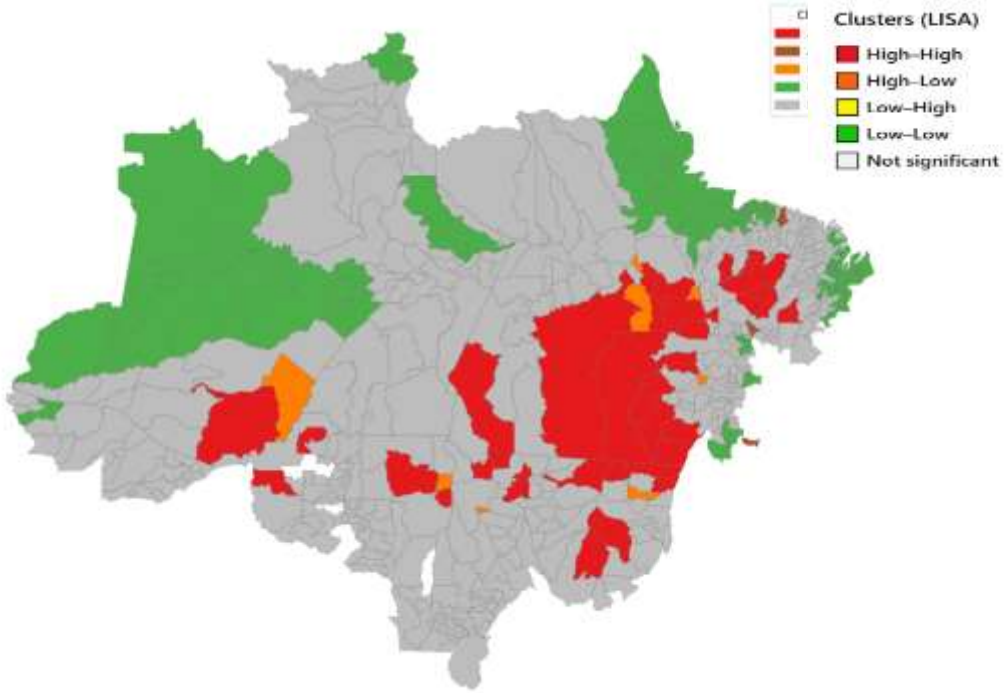
Graphic 6 – Legal Amazon Deforestation: Historical Series and ARIMA Projection



Source: Author's elaboration based on PRODES/INPE Amazon deforestation rate data (2000–2023).

In the map below, produced using the concept of spatial clustering, it is possible to identify the areas with the highest likelihood of increases influenced by TOC.

Figure 3 – Spatial Clustering Map – Mean Deforestation (LISA)



Source: Author's elaboration based on PRODES/INPE data (2000–2023) and Brazilian Forum on Public Security data (2024).

The interpretation of the clustering map is as follows:

Table 4 – Spatial Clustering Results: Deforestation – TOC

CLUSTER	SPATIAL INTERPRETATION	IMPLICATIONS FOR TOC AND DEFORESTATION
High-High	Municipality with high deforestation, surrounded by neighbors also exhibiting high deforestation.	Strong evidence of regional patterns of elevated deforestation, possibly reflecting coordinated TOC influence across contiguous areas. May indicate a consolidated route of illegal exploitation (e.g., timber, cattle, or drug trafficking).
High-Low	Municipality with high deforestation, surrounded by neighbors with low deforestation.	May indicate that TOC is acting in an isolated or recent manner in a specific area, generating a *hot spot* of deforestation outside traditionally affected regions. May represent a new front of expansion.
Low-High	Municipality with low deforestation, surrounded by neighbors with high deforestation.	Potential transition or buffer zone resisting TOC expansion. May involve municipalities with protected areas or stronger state presence, though at risk due to proximity.
Low-Low	Municipality with low deforestation and surrounded by neighbors also with low deforestation.	Area of relative environmental stability and territorial security. May indicate absence or low impact of TOC. Worthy of preservation and preventive policies.

Source: Author's elaboration.

4 DISCUSSION

The problem formulated for the development of this article was the following: **how does transnational organized crime impact illegal deforestation rates, with negative implications for the protection and sustainable future of the Amazon?**

The results of the qualitative analysis show that criminal organizations in the Amazon are already present in roughly 34% of the territory. The profitability achieved by transnational organized crime, whether through drug trafficking or the commission of environmental crimes (with estimated profits ranging from USD 110 to 281 billion per year)—enables reinvestment in the region, generating a convergence of illicit activities with a significant impact on deforestation, which becomes narco-deforestation. Federal Police data reveal, for example, a 66% interrelation between illegal deforestation and land grabbing, and a 32% interrelation with illegal logging.

The criminal convergence observed among deforestation, land grabbing, illegal logging and mining, fraud, and other illicit activities aligns with the concept of hybrid governance as exercised by transnational organized crime (TOC) in the Amazon. According to Pimenta *et al.* (2021, p. 7), hybrid governance can be understood as the presence of different sources of authority within the same space, where violence, rules, and moral conduct are administered by both legal and illegal actors. In this sense, TOC coexists and competes with the State, imposing specific rules on social conduct (Ferreira, 2023).

Hybrid governance manifests itself in illegal deforestation when TOC employs corruption to enable the activity, resorting, for example, to: the co-optation of public officials for the falsification of documents such as forest management plans and forest transportation permits (Instituto Igarapé, 2023, p. 11); forest origin documents (p. 12); the fraudulent issuance of artisanal mining permits, land ownership certificates, and other documents related to environmental crimes (p. 15); facilitation of the illegal mineral trade (p. 19); cattle "laundering" through the so-called triangulation process, whereby cattle are moved from illegal areas to legalized ones (p. 22); and enabling the illegal or irregular appropriation of public lands (p. 25), among many other "windows of opportunity."

Moreover, poverty and the lack of lawful economic opportunities – which could otherwise be fostered by the State – lead individuals and communities to align themselves with criminal practices (Marques, 2023, p. 14). Land conflicts, the marginalization of

traditional communities, and population flows further facilitate the commission of criminal acts (Gama; Barboza; Jesus, 2024, p. 9).

Other aspects that facilitate criminal convergence and hybrid governance in the Amazon include: (1) logistical capillarity and armed protection—criminal factions create or finance clandestine airstrips, informal ports, and violent protection networks, thereby reducing costs and risks for illicit environmental activities; (2) land laundering and speculative land accumulation—profits from drug trafficking and other illicit markets are reinvested in land and cattle, enabling land grabbing and the conversion of forests into pasture or cropland; and (3) co-optation and institutional capture—corruption in registries, licensing, enforcement, and notary offices to falsify documents while simultaneously weakening deterrence mechanisms.

From a qualitative perspective, it was observed that, beginning in the 1990s, the deforestation process in the Brazilian Amazon became increasingly linked to economic activities—particularly agricultural and livestock production, which required forest clearing to establish pasture for extensive cattle ranching or large-scale agriculture. This shift created a window of opportunity for criminal organizations operating in the region, especially those involved in drug trafficking, to launder profits derived from cocaine sales.

The results of the quantitative analysis indicate that municipalities with the presence of criminal organizations displayed higher average annual deforestation between 2000 and 2023 compared to those without such presence: approximately 1,434 hectares/year versus 1,035 hectares/year. This difference was found to be statistically significant (Welch's t-test, $p < 0.01$). This finding appears consistent with the qualitative assessment of ORCRIM activity in the Amazon, given the convergence of illicit activities such as deforestation, land grabbing of public lands, illegal logging, and illegal mining.

In the logistic model, the presence of criminal factions is associated with a higher likelihood that a municipality falls into the deforesting group (odds ratio 2.78, 95% CI 1.55–4.98), with an average marginal effect of roughly +15 percentage points, reinforcing the facilitating role of TOC in driving deforestation events.

The quantitative analysis was able to identify the likelihood that ORCRIM exert influence over illegal deforestation, in line with qualitative findings; however, the insufficiency of annual, organization-specific data suggests caution in interpreting the causal direction of this phenomenon.

Taken together, empirical evidence and existing studies support the argument that the presence of ORCRIM acts as a structural amplifier of deforestation risk—particularly where state capacity is low, illicit profitability is high, and logistical corridors reduce opportunity costs. Policies focused on such corridors, illicit revenue streams, and land governance are likely to yield greater returns than isolated sectoral interventions.

5 CONCLUDING REMARKS

Transnational organized crime (TOC) represents a high-impact threat to Brazil, generating concrete harm to Brazilian society—whether through narcotrafficking or through deforestation and its associated illicit activities, which form part of the criminal portfolio operating in the region.

Based on the quantitative study, it was found that, at present, TOC contributes to nearly 25% of the illegal deforestation activity in the Amazon. This impact has the potential to increase, as suggested by the spatial clustering analysis. From the qualitative perspective, "narco-deforestation" appears to result from the reinvestment of profits derived from criminal convergence in the Amazon and from the hybrid governance dynamics—where criminal actors compete with the State—that have become established in the region.

The findings suggest three main axes for addressing this situation: (1) strengthening interagency operations focused on commercial corridors, grounded primarily in financial intelligence and logistical control (airstrips, ports, dredges) along priority axes (Solimões, BR-163, BR-319); (2) reinforcing land governance and traceability—cleaning and verifying land registries, blocking land grabbing, and ensuring supply-chain traceability (cattle–timber–mineral), supported by financial and commercial sanctions; and (3) financial action targeting the flows associated with narco-deforestation (monitoring transactions linked to land, heavy machinery, fuel, and front persons), in coordination with international partners (EU, United States, Andean neighbors).

The data obtained in this study open pathways for future research concerning the extent of transnational organized crime's influence over deforestation in each subregion of the Brazilian Amazon, as well as the relative contribution of each illicit economic activity within the broader framework of criminal convergence.

At a time when the sovereignty of some nations is under threat—such as the kinetic challenge faced by Ukraine, or the rhetorical pressures directed at Denmark (in connection with Greenland)—it is not surprising that the Amazon may soon be framed as a strategic asset under dispute for various reasons: its vast freshwater reserves, its deposits of rare-earth elements, its valuable bioactive compounds, among others. In this context, the narrative of external intervention justified by deforestation and its global climate effects may become a convenient argument for certain international actors, posing risks to the future of the Brazilian Amazon.

Ultimately, it is clear that the protection and sustainable future of the Amazon are at stake, in a contest where those who possess power exercise it with little regard for the more vulnerable or less prepared.

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Geospatial indicator of illegal mining[1] fronts from the Mining Alert System (LOGAR) of CENSIPAM

Indicador geoespacial de frentes de garimpo a partir do Sistema de Alertas de Garimpo (LOGAR) do CENSIPAM

Indicador geoespacial de frentes de minería ilegal a partir del Sistema de Alertas de Minería (LOGAR) del CENSIPAM

Indicateur géospatial des fronts de l'orpaillage à partir du Système d'Alerte de l'Orpaillage (LOGAR) du CENSIPAM

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Abstract
This study presents a geospatial tool for identifying active illegal mining fronts in the Brazilian Legal Amazon, based on historical alerts from the LOGAR system (CENSIPAM). The Mining Front Index combines the spatial density and temporal persistence of alerts linked to illegal gold mining to detect areas with ongoing activity. The goal is to improve territorial monitoring and prioritize enforcement efforts, particularly in Indigenous Lands. Results demonstrate the index's effectiveness in capturing distinct patterns. In the Kayapó Indigenous Land, from 2023 to 2025, active fronts persisted despite a reduction in the number of alerts, including spatial shifts in activity. In the Yanomami Indigenous Land, the index recorded a peak in February 2023, followed by a sharp and sustained decline, likely reflecting the impact of government-led

[1] **Translator's note:**
For the purposes of this article, the term illegal mining is used as a translation of the Brazilian concept of *garimpo,* acknowledging that, in the Brazilian legal framework, gar*impo* may refer to both legal and illegal small-scale mining activities. The use of illegal mining reflects the predominant empirical context addressed in the analysis.

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removal operations. The methodology, based on satellite imagery and GIS, is practical and replicable. It supports public policy, enhances interagency coordination, and guides strategic acquisition of high-resolution imagery. The index enables smarter, more targeted surveillance, and is capable of tracking illegal mining trends across vulnerable regions of the Amazon.

Keywords: Legal Amazon; illegal activities; remote sensing; deforestation; PlanetScope.

Resumo

Este trabalho apresenta uma ferramenta geoespacial para identificar frentes ativas de garimpo na Amazônia Legal, com base em alertas históricos do sistema LOGAR (CENSIPAM). O Índice de Frente de Garimpo (IFG) combina a concentração espacial e a persistência temporal de alertas associados à mineração irregular, permitindo detectar áreas com atividade contínua. A proposta visa otimizar o monitoramento territorial e priorizar ações de fiscalização, especialmente em Terras Indígenas. Os resultados mostram que o IFG é eficaz para captar dinâmicas distintas. Na TI Kayapó, entre 2023 e 2025, mesmo com redução no número de alertas, foram identificadas frentes persistentes e realocação espacial da atividade. Na TI Yanomami, observou-se um pico em fevereiro de 2023, seguido por queda acentuada nas frentes. A metodologia, baseada em sensoriamento remoto e SIG, é prática, replicável e útil para apoiar políticas públicas, coordenar ações interagências e priorizar aquisição de imagens. O IFG contribui para uma vigilância mais inteligente e estratégica, capaz de acompanhar a evolução do garimpo irregular em contextos de alta vulnerabilidade.

Palavras-chave: Amazônia Legal; Ilícitos; sensoriamento remoto; desmatamento; PlanetScope.

Resumen

Este trabajo presenta una herramienta geoespacial para identificar frentes activos de minería ilegal en la Amazonía Legal, basada en alertas históricas del sistema LOGAR (CENSIPAM). El Índice de Frente de Minería (IFM) combina la concentración espacial y la persistencia temporal de alertas asociadas a la minería irregular, lo que permite detectar áreas con actividad continua. La propuesta busca optimizar el monitoreo territorial y priorizar acciones de fiscalización, especialmente en Tierras Indígenas. Los resultados muestran que el IFM es eficaz para captar dinámicas distintas. En la TI Kayapó, entre 2023 y 2025, aun con la reducción en el número de alertas, se identificaron frentes persistentes y reubicación espacial de la actividad. En la TI Yanomami, se observó un pico en febrero de 2023, seguido de una fuerte disminución de los frentes, reflejando el probable efecto de las operaciones de desintrusión. La metodología, basada en teledetección y SIG, es práctica, replicable y útil para apoyar políticas públicas, coordinar acciones interinstitucionales y priorizar la adquisición de imágenes. El IFM contribuye a una vigilancia más inteligente y estratégica, capaz de acompañar la evolución de la minería ilegal en contextos de alta vulnerabilidad.

Palabras clave: minería ilegal; Amazonía; geointeligencia; teledetección; SIG.

Résumé

Ce travail présente un outil géospatial destiné à identifier les fronts actifs d'extraction minière illégale dans l'Amazonie légale, à partir d'alertes historiques du système LOGAR

(CENSIPAM). L'Indice de Front de Garimpo (IFG) combine la concentration spatiale et la persistance temporelle des alertes liées à l'exploitation minière irrégulière, permettant ainsi de détecter les zones d'activité continue. La proposition vise à optimiser le suivi territorial et à prioriser les actions de contrôle, en particulier dans les Terres Indigènes. Les résultats montrent que l'IFG est efficace pour capter des dynamiques distinctes. Dans la Terre Indigène Kayapó, entre 2023 et 2025, malgré une diminution du nombre d'alertes, des fronts persistants et une relocalisation spatiale de l'activité ont été identifiés. Dans la Terre Indigène Yanomami, un pic a été observé en février 2023, suivi d'une baisse marquée des fronts. La méthodologie, fondée sur la télédétection et les SIG, se révèle pratique, réplicable et utile pour soutenir les politiques publiques, coordonner les actions interinstitutionnelles et prioriser l'acquisition d'images. L'IFG contribue à une surveillance plus intelligente et stratégique, capable de suivre l'évolution du garimpo illégal dans des contextes de forte vulnérabilité.

Mots-clés : Amazonie légale ; activités illicites ; télédétection ; déforestation ; PlanetScope.

1 INTRODUCTION

Mining in Brazil dates back to the colonial period, with the expedition of Martim Afonso de Sousa sent by Portugal to search for gold, silver, and precious stones. In 1549, Governor-General Tomé de Sousa began the exploitation of seashells in the Bay of All Saints, used in the production of lime for construction. In the 17th and 18th centuries, with the discovery of gold in Minas Gerais, Brazil stood out globally, producing about 50% of the world's gold and diamonds in the so-called Gold Cycle. In 1728, with the depletion of deposits in Mato Grosso, exploration advanced to the Upper Amazon and the Northern region. During World War II, the country became a supplier of strategic minerals such as mica, quartz, tungsten, tantalum, zircon, beryl, manganese, and iron. During this period, the Vale do Rio Doce Company was created to meet the demand of the USA and the United Kingdom. Today, Brazil is the sixth largest producer of non-fuel minerals in the world (Machado; Figueirôa, 2001).

In parallel with large-scale mineral extraction, artisanal and small-scale mining (ASM) and *garimpo* activities also exist, which can be irregular or regular, when carried out under the Artisanal Mining Permit (PLG), according to Law No. 7805/1989. Illegal mining has grown by 1200% in Brazil over the last four decades, especially in the Amazon, where approximately 91% of Brazil's illegal mining activity occurs (Siqueira-Gay; Sánchez, 2021; Mataveli *et al.*, 2022; Cortinhas Ferreira Neto *et al.*, 2024). From a legality perspective, Cortinhas Ferreira Neto *et al.* (2024) show that almost 80% of the mining that occurred in 2022 showed signs of illegality. Illegal mining promotes irreversible social and environmental impacts. According to Lobo *et al.* (2018), the Amazon accounts for about 80% of South American mercury (Hg) pollution in the environment, with Hg being ubiquitous and dynamic throughout the region.

Due to the persistence of Hg in the food chain, exposure, especially human exposure, to the toxic form of this element does not depend on proximity to the polluting source. The consumption of Methylmercury levels are two to six times higher than safe doses in some Amazonian regions.

The Legal Amazon region has the lowest Human Development Index in Brazil (PNUD, 2013). The socioeconomic vulnerability of the populations in this region is aggravated by the growing, and recent, presence of illegal mining. It is estimated that about 40% of illegal mining operations are five years old or less. This percentage rises to 62% when mining areas within indigenous territories are analyzed (Cortinhas Ferreira Neto *et al.*, 2024). With the rapid increase in the irregular extraction of minerals, mainly gold, social conflicts in the Amazon have also increased. Haslam and Tanimoune (2016) found a relationship between the intensity of conflicts arising from illegal mining and social vulnerability, where the greater the poverty and precariousness of the local infrastructure, the more intense the effects of mining. Formed by a mosaic of different social contexts such as riverside communities, extractivists, fishermen, family farmers, *quilombola* communities, and indigenous peoples, the Amazon is a priority area for combating and controlling illegal mining.

Mineral exploitation in Indigenous Lands (ILs) by invaders constitutes a serious socio-environmental problem affecting a significant portion of these territories in Brazil. In 2021, illegal mining activities occurred in 17 ILs, representing the direct conversion of an area of approximately 200 km², which corresponds to about 5% of the 332 officially recognized Indigenous lands. Although the direct conversion is relatively small, the indirect impacts can reach more than a third of the area of some Indigenous Lands, such as 33.4% in the Kayapó IL, 31.4% in the Munduruku IL, and 34.4% in the Yanomami IL (Da Silva *et al.*, 2023).

Remote sensing is a set of techniques for obtaining information about the Earth's surface without direct contact. Sensors can be optical, operating in the visible and infrared spectrum and are passive because they depend on solar radiation, or microwave, which are active because they emit their own radiation and allow data acquisition even without sunlight or in the presence of clouds (Liu, 2015). In the context of environmental monitoring, these technologies play a fundamental role, especially in regions of high biodiversity and vast territorial extent, such as the Legal Amazon. The integrated use of active and passive sensors allows the detection, analysis, and monitoring of various environmental and anthropogenic processes, such as deforestation, fires, floods, construction of clandestine airstrips, presence of vessels, and illegal mining activity. These technologies enable the generation of large-scale data, with high

temporal frequency and access to hard-to-reach areas, contributing significantly to the formulation of public policies, enforcement actions, and environmental conservation strategies.

Monitoring areas of illegal mining presents several challenges, especially due to the small scale at which these activities occur, often covering areas smaller than one hectare. These limited dimensions require the use of medium to high spatial resolution images (equal to or less than 20 meters) for adequate detection. Another complicating factor lies in the complexity of the Amazonian hydrographic networks, where mining activity can occur in both clean and turbid water environments, as well as developing on riverbanks. This variability contributes to the generation of spectral signatures similar to those of exposed soils, making it difficult to accurately differentiate between natural areas and areas impacted by mining, especially when using conventional optical remote sensing (Lobo *et al.*, 2018).

LOGAR (Location of Mining Sites) was created by CENSIPAM to detect, analyze, and monitor illegal mining activities in the Legal Amazon, evolving from *ProAE-Inteligência* (Special Areas Monitoring Program – Intelligence), initiated in 2008. Reformulated in 2014 and updated in 2018, it began operating as a Geographic Information System for Intelligence, integrating data from *DETER/INPE* and PlanetScope of the Brazil MAIS Program, with a centralized database to identify typical patterns of illegal mining. The LOGAR database, composed of polygons of illegal mining activities since 2005, represents a valuable historical basis for understanding the spatial and temporal evolution of illegal mining in the Legal Amazon. However, the distinction between historical illegal mining sites and active fronts, that is, areas with illegal mining activity or emerging in the present, is essential to guide environmental control, public security, and territorial management actions in a strategic and efficient manner.

From an enforcement perspective, identifying illegal mining fronts allows for the optimization of human and logistical resources, prioritizing action in areas where environmental and social impact is ongoing or about to intensify. This capability is crucial for planning land clearing operations, especially in Indigenous Lands and Conservation Units, where the presence of illegal miners compromises the integrity of traditional populations and sensitive ecosystems. Furthermore, up-to-date information on active fronts supports decisions regarding the use of ultra-high-resolution commercial imagery and SAR (Synthetic Aperture Radar) sensors, allowing for prioritization of coverage of the most critical regions and reducing costs associated with redundant or unnecessary imaging.

Another relevant aspect is the generation of geospatial intelligence for interagency actions, such as those coordinated by the Ministry of Justice, IBAMA (Brazilian Institute of Environment and Renewable Natural Resources), ICMBio (Chico Mendes Institute for Biodiversity Conservation), and the Armed Forces. By anticipating the movement of illegal mining activities, it is possible to act preventively, avoiding the consolidation of illegal infrastructure (barges, airstrips, camps) and the formation of logistical support chains. There are also gains for monitoring socio-environmental risks, such as mercury contamination, river siltation, and the expansion of deforestation associated with mining. In strategic terms, the ability to detect active mining fronts reinforces the role of LOGAR as a territorial intelligence tool aimed at protecting the Amazon and governing its natural resources. Therefore, this work aims to present a simplified and accessible methodology for identifying illegal mining fronts, called the IFG (Mining Front Index), based on the database of deforestation alerts associated with mining activity. The Kayapó and Yanomami Indigenous Lands were used as pilot areas.

2 MATERIAL AND METHODS

2.1 STUDY AREA

The study was conducted within the boundaries of the Legal Amazon (AL), a region encompassing nine Brazilian states and occupying approximately 5,015,068.18 km², equivalent to 59% of the national territory. In terms of biomes, the AL is predominantly composed of Amazon rainforest (approximately 80%), followed by the Cerrado with 15% and the Pantanal with 1% (IBGE, 2003). From a climatic point of view, the region is distributed across three Köppen classifications: Af (humid equatorial climate), predominant in the northwest, with average temperatures between 25 °C and 28 °C and average annual rainfall (AWF) above 2,000 mm, possibly exceeding 3,000 mm, without a well-defined dry season; Am (monsoon climate), which extends from the western to the northeastern portions of the AL, has a short dry season (June to August), but maintains a high AWF, between 1,600 mm and 3,000 mm; and Aw (tropical savanna climate), with strong seasonality, a dry winter (from May to September), and average rainfall varying between 1,000 mm and 1,500 mm (Dubreuil et al., 2018). These variations reflect the environmental diversity that characterizes the region.

From a socio-environmental perspective, the Legal Amazon (LA) holds one of the greatest biodiversities on the planet and a wide socio-cultural diversity. LA is home to more than half of the country's indigenous population, approximately 51.2% (IBGE, 2023). There are

424 Indigenous Lands in the Amazon where 46% of the indigenous people of LA live, and which together account for approximately 22% of the LA's area (1,153,444 km²) (IBGE, 2023). Regarding *quilombola* populations, the 2022 Demographic Census of IBGE counted 426,449 *quilombola* people in the municipalities of LA – almost a third (32.11%) of the total of this population in the country, of which 80,899 live in officially demarcated *Quilombola* Lands, representing 48.38% of the national total of this group. The 2022 Demographic Census also provided robust data on indigenous peoples and extractive communities, highlighting their significant relevance to the sustainable management of natural resources. Currently, there are 41 federal Extractive Reserves in the Legal Amazon, inhabited by traditional populations such as rubber tappers, Brazil nut gatherers, and other groups linked to extractive lifestyles.

The survey also identified that 11.8 million people live in Conservation Units in Brazil, corresponding to 5.8% of the total population. Of this universe, traditional peoples and communities represent significant portions: *quilombola* communities total 282,258 people (2.39% of the population residing in Conservation Units) and indigenous people total 132,804 people (1.12%). Almost all (98.73%) of the people living in Conservation Units are in sustainable use areas, such as Environmental Protection Areas and Extractive Reserves. The 2022 Census data also reveal social challenges in these areas: the illiteracy rate among residents of Conservation Units is 8.84%, above the national rate of 7.00%. Among the 9,245,172 residents aged 15 or older in these areas, 817,383 are illiterate (IBGE, 2023). Similarly, riverside populations stand out, maintaining a strong link with the dynamics and "health" of the rivers, and are officially recognized as traditional communities by Decree No. 6,040/2007, which establishes the National Policy for the Sustainable Development of Traditional Peoples and Communities (PNPCT).

2.2 DESCRIPTION OF THE ALERT DATABASE AND LOGAR METHODOLOGY

The *sig_alertas* is an internal relational database of CENSIPAM, based on PostgreSQL and designed to store and manage geospatial data used by the operational area of the institution's different Centers. Deployed on a server on an internal network, the system allows both local and external access via VPN, guaranteeing the confidentiality and authenticity of the data for authorized users. The database is structured to support analytical and operational operations related to territorial monitoring of the Legal Amazon, making use of geographic extensions such as PostGIS for advanced manipulation of spatial information. The *sig_alertas* is accessed

directly by Geographic Information System (GIS) tools, specifically QGIS, allowing the visualization, analysis, and editing of spatial data in real time by authorized analysts and technicians.

The methodology applied in LOGAR is based on the integration of remote sensing technologies, geoprocessing, and an analytical routine structured in two main phases: validation and review. The LOGAR area of coverage corresponds to the Brazilian Legal Amazon, subdivided for operational purposes among the Regional Centers of Belém (CR-BE), Manaus (CR-MN), and Porto Velho (CR-PV), each responsible for monitoring the states under its jurisdiction (Figure 1). Each analyst is assigned to a fixed set of satellite scenes, ensuring that the entire Legal Amazon is analyzed at least once a year.

Figure 1 – Subdivision of the jurisdiction of the states of the Legal Amazon of each Regional Center (CR): Manaus (MN), Belém (BE) and Porto Velho (PV) of the Management and Operational Center of the Amazon Protection System (CENSIPAM/MD). The two Indigenous Lands analyzed in this study (Kayapó and Yanomami) are highlighted

Source: Designed by the authors.

The main input data used for detecting illegal mining targets are deforestation alerts associated with mining activity, originating from two main systems: DETER (Real-Time Deforestation Detection), from the National Institute for Space Research (INPE), and the alert system based on the PlanetScope satellite constellation, linked to the Brazil MAIS program of the Ministry of Justice and Public Security. In Brazil MAIS, automatic processing uses PlanetScope images (3 m) to detect changes in land cover. The workflow involves radiometric and geometric corrections, cloud removal, and application of the change detection algorithm.

Spectral indices such as NDVI, NBR, and NDWI are calculated, comparing time series to identify abrupt drops in vegetation and the presence of turbid water typical of illegal mining. The method is pixel-oriented, with predominant use of unsupervised classification to highlight areas of change and then spectral rules to refine the polygons. The detected areas are transformed into vectors and automatically classified, serving as alerts. INPE's DETER system operates with medium-resolution sensors (250 m – MODIS/Terra and Aqua; 64 m – WFI/CBERS-4; 60 m – WFI/Amazonia-1), prioritizing rapid large-scale detection. The processing applies multi-temporal change detection algorithms, supported by indices such as NDVI, EVI, and NBR, associated with supervised classification techniques and object-oriented segmentation. This object-oriented approach allows for the differentiation of geometric patterns of deforestation (e.g., regular agricultural polygons versus irregular clearings), generating alerts with greater spatial coverage and near-daily periodicity. Despite its lower resolution, DETER ensures systematic and broad coverage, serving as an agile and complementary monitoring tool to Brasil MAIS, which focuses on detecting smaller-scale changes. In addition to these two sources, CENSIPAM supplements its coverage with data from other Earth observation sensors, such as CBERS, LANDSAT, SENTINEL, and SAR sensors, allowing flexibility in image selection according to cloud conditions, spatial resolution, and orbital revisit.

The analytical process follows a daily routine, beginning with analysts connecting to the geospatial database via the QGIS platform. Newly generated alerts are then loaded and displayed as vector layers, which are cross-referenced with the cartographic database of Indigenous Lands, Conservation Units, and mining titles from the National Mining Agency (ANM). Polygons identified with evidence of illegal mining activity are then classified according to their legality based on spatial overlap with these reference layers.

Initial validation is performed based on visual interpretation of high-resolution images (Planet), considering typical characteristics of mining sites, such as clearings with irregular outlines, the presence of structures like ramps and barges, and evidence of turbidimetry in water bodies. Confirmed targets proceed to the review phase, which consists of cross-checking by a second analyst. After this double check, the records are consolidated into the final database.

LOGAR also has proactive capabilities: in regions without continuous coverage or outside the reach of automatic alerts, CENSIPAM conducts independent searches through systematic image analysis, ensuring comprehensive geospatial coverage. In this way, LOGAR represents a robust model for territorial surveillance and the production of geospatial intelligence aimed at combating illegal mining.

2.3 DEFINITION OF MINING FRONT AND DESCRIPTION OF THE MINING FRONT INDEX (IFG)

Based on the information available in LOGAR, it was possible to propose a simple and accessible way to identify mining fronts, calculated from the estimate of the Mining Front Index (Equation 1).

$$\text{Mining Front Index (IFG)} = \frac{Area/Time}{T - T_{today}} \quad (1)$$

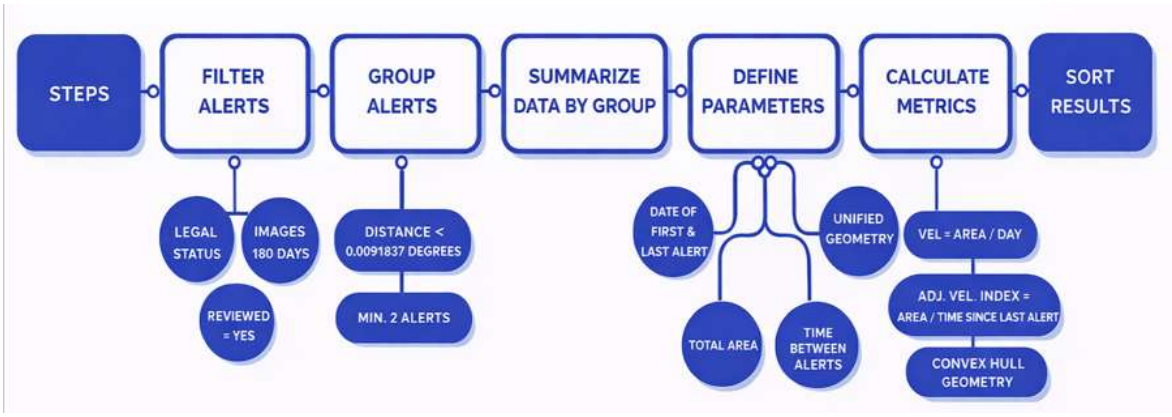
Where “Area” is the sum of the areas of the alerts, “Time” is the time interval between the date of the first alert and the last, while “T” represents the date of the last alert and “Today” is today's date.

The code creates a materialized view that groups alerts of illegal mining registered in the last 180 days and calculates an index of the expansion rate of these areas. Spatial clustering is used to identify groups of nearby alerts and, for each group, it calculates the total area, the time interval between alerts, the time since the last alert until today, and generates a representative geometry. The view highlights the groups with the highest growth rate, allowing for the prioritization of critical regions for inspection.

Main steps (Figure 2):

1. Filter recent and illegal alerts (pol): Selects only illegal mining alerts with "ILLEGAL" status, reviewed (reviewed = 'S'), with images within the last 180 days. Includes information such as alert date, status name, geometry, and area;
2. Spatially groups alerts (groups): Uses the st_clusterdbscan function to group alerts that are close to each other (distance < 0.00181237 degrees or 200 meters), forming alert groups with at least 2 occurrences.
3. Summarize the data by group (data): For each group;
4. Calculate: The date of the first and last alert; Total area (sum of the areas of the alerts); Time between alerts; Time since the last alert until today; Unified geometry of the group;
5. Calculate metrics: For each valid group (time_diff > 0 and group IS NOT NULL), calculate: vel: rate of increase of deforestation associated with illegal mining (area per day). ind_vel: rate index adjusted for time since the last alert. Convex hull geometry to represent the total area. Results are ordered by rate index in descending order.

Figure 2 – Flowchart of the steps used to define mining fronts and calculate the Mining Front Index (IFG)



Source: Designed by the authors.

3 DEVELOPMENT

3.1 RESULTS

The Mining Front Index (IFG) was developed as an analytical tool to identify areas with persistent and concentrated recent alerts of illegal mining, going beyond simply counting occurrences. By combining the spatial density and temporal continuity of alerts, the indicator allowed the detection of mining fronts that remain active over time (last 180 days), even if the raw number of alerts varies. This approach offers a more qualified understanding of illegal mining dynamics, allowing for targeted monitoring and prioritization of critical areas for enforcement actions.

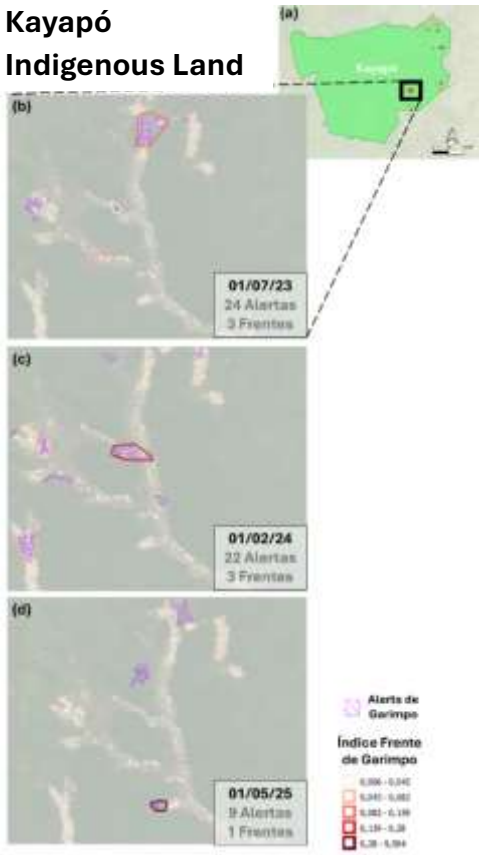
The sequence of images (Figure 3) shows the dynamics of mining activity within the Kayapó Indigenous Land (Figure 3a) over three distinct periods, highlighting both the number of alerts and the presence and intensity of mining fronts. On July 1, 2023 (Figure 3b), 24 alerts and three active fronts were recorded, with areas demarcated in different intensities of red according to the IFG, a tool that synthesizes the degree of spatial concentration and persistence of alerts. The most active fronts showed high IFG values (up to 9.564), evidencing growing illegal mining areas.

In the second period, on February 1, 2024 (Figure 3c), the number of alerts decreased slightly to 22, with three fronts still identified. However, there was a spatial reorganization of these fronts, with a more prominent concentration in the central portion of the image, associated with a polygon with an intermediate-high IFG (between 0.139 and 0.28). This displacement,

captured by the IFG, reveals the usefulness of the tool to identify not only the number of alerts, but also mobility patterns and possible expansion or contraction of mining fronts over time.

The last image (Figure 3d), from May 1, 2025, shows a sharp drop in the number of alerts (nine) and a significant reduction in the number of active fire fronts, leaving only one. The marked areas indicate low intensity, with values in the lower ranges of the IFG. The functionality of the IFG becomes evident in this scenario: even with few alerts, it allows differentiation between sporadic activities and those that, although punctual, concentrate continuous efforts. This differentiation is crucial for guiding territorial monitoring and response strategies.

Figure 3 – Evolution of illegal mining alerts and identification of mining fronts in the Kayapó Indigenous Land (a) in three periods: (b) 01/07/2023, (c) 01/02/2024 and (d) 01/05/2025. The areas shaded in purple indicate the alerts detected, while the solid outlines represent the mining fronts identified based on the Mining Front Index (IFG). The intensity of the polygon coloring varies according to the IFG value. The intensity of the polygon coloring varies according to the IFG value. The intensity of the polygon coloring varies according to the IFG value. A progressive reduction is observed in both the number of alerts and active fronts throughout the analyzed period

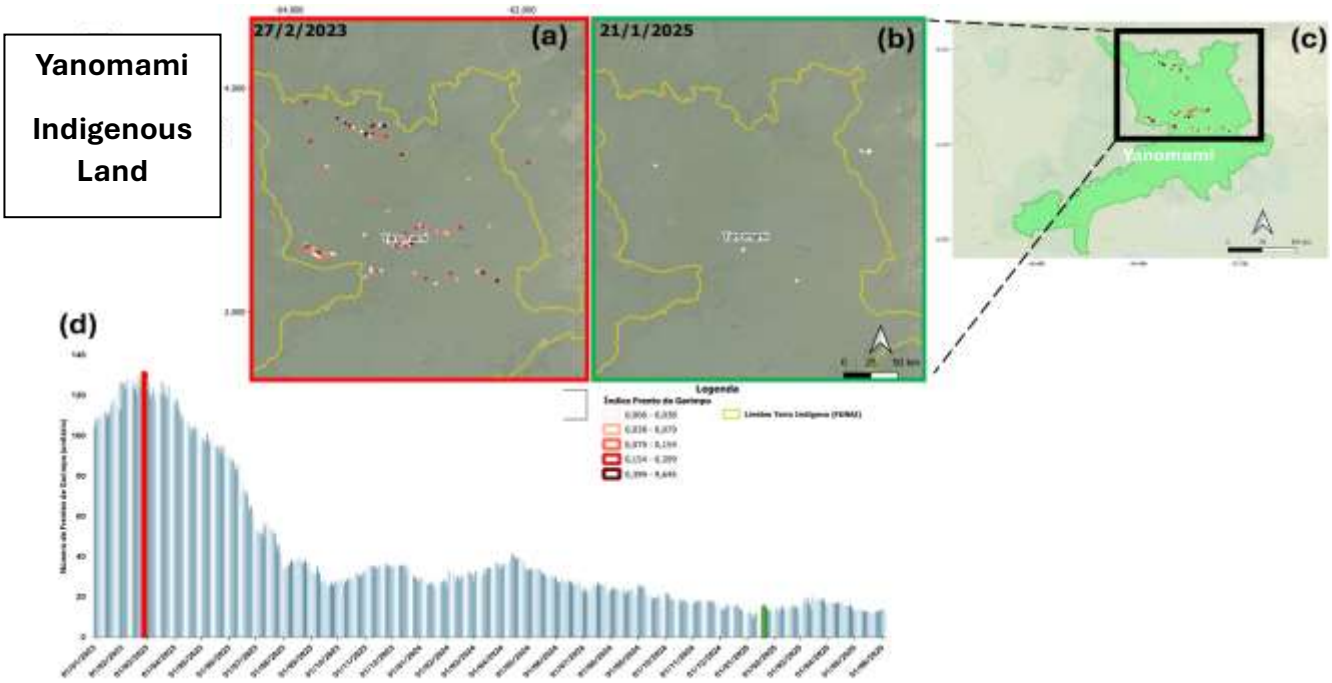


Source: Designed by the authors.

Additionally, a historical case study was conducted during the period from 2023 to 2025 in the Yanomami Indigenous Land (Figure 4), known for being under strong pressure from illegal mining and subsequent intense repression of this illicit activity. In the Yanomami Indigenous Land, the temporal data reveal a particular scenario, with a peak in mining activity in February 2023, followed by a sharp and continuous decline. The rapid reduction of mining fronts after the peak indicates an immediate and probably coordinated response to government intervention, such as operations to remove invaders widely publicized in the media during this period. The stability observed in the low levels of activity from the second half of 2023 suggests the effectiveness of the actions taken, at least within the analyzed time frame.

The maps (figure 4a-b) corroborate this trend: on February 27, 2023, mining fronts are concentrated mainly in the central portion of the Indigenous Land, with some areas of high intensity. In contrast, on the map of January 21, 2025, there is practically no record of active fronts. The almost complete elimination of mining activity detectable by remote sensing may represent a significant result of territorial control.

Figure 4 – Comparative maps of the spatial distribution of mining fronts referring to the maximum (a) and minimum (b) of mining activity in the Yanomami Indigenous Land (c). The polygons are classified according to the mining front index (IFG). In (d) the time series of the number of mining fronts detected in the Yanomami TI between January 2020 and June 2025 is presented. The red line indicates the peak date of mining activity, and the green line the date of lowest recorded activity



Source: Designed by the authors.

3.2 DISCUSSION

Remote sensing has been a strategic ally in detecting land-use change, whether deforestation for timber or associated with illegal mining. In a review by Kozinska and Górniak-Zimroz (2021), the authors evaluate methods for detecting illegal open-pit mining, highlighting techniques based on remote sensing. The most common techniques were image classification: supervised, unsupervised, and hybrid. The most used data sources were free satellite images (Landsat, Sentinel). However, the low resolution hindered the detection of small sites, characteristic of illegal mining and prospecting, requiring higher-resolution images, sometimes paid images. Finally, the authors conclude that the choice of the ideal method depends on data availability, terrain characteristics, and technological resources, but the two most accurate were the CLASlite system (94%) and image fusion with spectral indices (91.1%). CLASlite relies on image quality and performs best in tropical regions, while spectral index fusion requires careful band selection and can be sensitive to seasonality and spectral noise.

Regarding the transnational Amazonian biome, recent studies seek to propose and improve methods for alerting illegal mining. The study by Becerra *et al.* (2024) presents a near real-time alert system to detect deforestation due to illegal mining in the Peruvian Amazon using Sentinel-1 SAR data. In this study, 185,460-pixel alerts were detected between February and December 2022, totaling 1,864 ha of mining, with an accuracy of 99.98%. Finally, the authors concluded that the RAMI platform is effective for continuous monitoring, even under cloud cover, supporting rapid enforcement actions. In Brazilian territory, Mataveli *et al.* (2022) associate collection 6 of the MapBiomas project, which uses Landsat satellite images classified by the Random Forest algorithm, with the Mann–Kendall test to detect the growth of illegal mining within Indigenous Lands. The authors found an increase of approximately 1200% between 1985 and 2020, with a growing trend. Finally, the study highlights the challenge of enforcement and the urgent need for investment in effective public policies, pointing out that demarcated Indigenous Lands are vulnerable. Considering this increase in illegal mining in Indigenous Lands, especially in the Kayapó, Munduruku, and Yanomami Indigenous Lands, Da Silva *et al.* (2023) identified areas of high mining interest, roads, and clandestine airstrips as the main vectors associated with illegal mining.

In terms of challenges and opportunities in the remote and continuous detection of illegal mining in the Legal Amazon, a robust database is fundamental. Specifically, a database of illegal mining alerts with an extensive time series, systematic validation, and multiple

information sources is crucial for the development of reliable and operational metrics, such as an index of illegal mining growth. The integration of alerts generated by different image classification methods with visual inspections carried out by analysts allows for greater consistency in the records and greater control over data quality. The diversity of sources reduces dependence on a single detection method, minimizing biases and increasing the robustness of the analyses. Without a database with these characteristics, derived indicators tend to present limitations in terms of temporal precision, comparability, and applicability.

Due to the atmospheric and climatic conditions of tropical forests, especially in much of Latin America, multisensor remote sensing approaches are growing, particularly the use of active sensors such as radar. In the study by Forkuor, Ullmann, and Griesbeck (2020), time series data obtained by the Sentinel-1 sensor were used to monitor small areas of artisanal mining located in Southwest Ghana. The dataset consisted of 155 images, collected between July 2015 and April 2019. However, the analysis was partially limited by the presence of atmospheric interference, resulting in the exclusion of low-quality scenes. Although Synthetic Aperture Radar (SAR) data offer advantages for monitoring in regions with high cloud cover, the results of Forkuor, Ullmann, and Griesbeck (2020) demonstrated a sensitivity of the Sentinel-1 C-band to intense cloudiness events.

Cloud cover in the Amazon varies according to the climate of the sub-regions (Af, Am, and Aw according to Köppen), directly affecting visibility for optical sensors. Wetter Af and Am regions have greater cloud cover, while drier Aw areas offer better observation conditions, especially during the dry season. In this context, the results indicate that the effectiveness of optical detection systems, such as those used by DETER and the Brasil MAIS program, is directly limited by climatic conditions, especially the high cloud cover associated with regions classified as Af and Am, where alert detection is slower or fails (Silva *et al.*, 2020; Albuquerque *et al.,* 2025). The performance of Brasil MAIS alerts improves during the dry months (May to September), when there is less convective activity, and worsens between November and March, a period of intense rainfall, when cloud cover reduces the number of useful images, even with the high revisit frequency of Planet satellites (Albuquerque *et al.*, 2025). The DETER system presents similar limitations, facing persistent cloud cover during the rainy months, coinciding with increased illegal logging activity, which ends up not being detected (Silva *et al.*, 2020). As an alternative, sensors with SAR (Synthetic Aperture Radar) technology suffer less atmospheric interference and can operate in a wider variety of weather conditions.

The illegal mining front identification tool represents a strategic advancement for monitoring and combating illegal mining in the Legal Amazon. By integrating geospatial alerts and growth indices, it allows for more precise location, analysis, and monitoring of active or expanding areas. Its uses extend beyond enforcement, offering support for tactical actions, interagency planning, academic studies, and public policy formulation. Identifying illegal mining fronts allows for targeted acquisition of high-resolution commercial images, optimizing resources and avoiding redundant imaging. Regions with high growth rates of mining activity can be prioritized for more frequent coverage or with specific sensors, such as SAR radars, expanding detection and response capabilities in near real-time. Another application of the tool is in the planning and logistics of field enforcement operations. With updated data on illegal mining fronts, agencies such as IBAMA, ICMBio, the Federal Police, and the Armed Forces can coordinate joint actions more efficiently, reducing risks and maximizing the impact of interventions. The data extracted from the tool also serve as a basis for studies on the spatial and temporal dynamics of illegal mining in the Amazon. It is possible to identify patterns of expansion, relationships with infrastructure (roads, rivers, clandestine airstrips), activity cycles, and specific territorial profiles, contributing to more in-depth socio-environmental and regional analyses.

The Mining Front Index (IFG) has as its main limitation its direct dependence on the quality and robustness of the database used. The reliability of the results is conditioned both by the confirmation and improvement of the alert itself, and by possible data cross-referencing, as in the case of categorizing the legality of mining. The latter depends on information provided by the National Mining Agency (ANM), whose data crossing has already shown inconsistencies and is in the process of improvement, reinforcing the need for constant validation and updating of reference sources.

Finally, among the upcoming challenges are improving the tool by calibrating the time window and distance radius to better represent the growth dynamics of illegal mining, as well as evaluating which Index value best represents the priority mining fronts for monitoring. In the medium and long term, improvement can occur through the use of predictive algorithms and greater integration of socioeconomic, climatic, and geological data. Key questions include: What vectors are driving new fronts? What is the relationship between active fronts and protected territories? How to predict areas under imminent risk of illegal occupation?

4 FINAL CONSIDERATIONS

The Mining Front Index (IFG) has proven to be an efficient and accessible tool for spatial and temporal monitoring of illegal mining activity in the Legal Amazon. By combining density and permanence of alerts, the index allows the identification of fronts of continuous activity, even in scenarios with low alert frequency, making it especially valuable for strategic enforcement actions. Case studies in the Kayapó and Yanomami Indigenous Lands demonstrated the method's sensitivity in detecting both the persistence and retraction of illegal activities in response to control policies. Furthermore, the tool can support inter-institutional decisions, optimize the use of commercial images, and inform resource allocation. Although the IFG is limited by its dependence on the quality of databases, both in confirming alerts and in cross-referencing for categorizing legality, its application can be expanded to other regions of the Amazon, contributing to the strengthening of environmental governance and the protection of traditional territories against the increasing pressure of illegal mining.

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Amazonia: climate issue, security and defense in the future

Amazônia: questão climática, segurança e defesa no futuro

Amazonia: cuestión climática, seguridad y defensa en el futuro

Amazone : question climatique, sécurité et défense à l'avenir

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Abstract
This article analyzes the growing link between the climate issue and the security and defense domains, with emphasis on the Amazon region. It starts with the recognition that the natural environment, especially the Amazonia, has become a central element in contemporary geopolitical disputes. The objective is to investigate how the climate crisis can be securitized, becoming an instrument of international pressure and a risk to national sovereignty. The research adopts a qualitative approach, with literature review and documentary analysis of strategic and normative frameworks. The results indicate that, although Brazil has a robust environmental legal framework, the absence of a grand national strategy integrating security, development, and the climate issue may render the Brazilian state vulnerable to environmental instrumentalization by foreign powers. It is concluded, therefore, that it is necessary to strengthen sustainable public policies and defense strategies that incorporate the climate variable, all included in a grand national strategy that confers synergy to the process.

Keywords: securitization; environmental geopolitics; strategic sustainability; sovereignty; grand strategy.

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Resumo
Este artigo analisa a crescente vinculação entre a questão climática e os domínios da segurança e defesa, com ênfase na região amazônica. Parte-se do reconhecimento de que o meio ambiente natural, especialmente a Amazônia, tornou-se elemento central nas disputas geopolíticas contemporâneas. O objetivo é in vestigar como a crise climática pode ser securitizada, convertendo-se em instrumento de pressão internacional e risco à soberania nacional. A pesquisa adota uma abordagem qualitativa, com revisão bibliográfica e análise documental de marcos estratégicos e normativos. Assim, os resultados indicam que, embora o Brasil possua um arcabouço jurídico ambiental robusto, a ausência de uma grande estratégia nacional que integre segurança, desenvolvimento e a questão climática, pode tornar vulnerável o Estado brasileiro à instrumentalização ambiental por potências estrangeiras. Conclui-se, portanto, que é necessário reforçar políticas públicas sustentáveis e estratégias de defesa que incorporem a variável climática, inclusas todas em uma grande estratégia nacional que confira sinergia ao processo.

Palavras-chave: securitização; geopolítica ambiental; sustentabilidade estratégica; soberania; grande estratégia.

Resumen
Este artículo analiza la creciente vinculación entre la cuestión climática y los ámbitos de la seguridad y la defensa, con énfasis en la región amazónica. Parte del reconocimiento de que el medio ambiente natural, especialmente la Amazonia, se ha convertido en un elemento central en las disputas geopolíticas contemporáneas. El objetivo es investigar cómo la crisis climática puede ser securitizada, convirtiéndose en un instrumento de presión internacional y en un riesgo para la soberanía nacional. La investigación adopta un enfoque cualitativo, con revisión bibliográfica y análisis documental de marcos estratégicos y normativos. Los resultados indican que, aunque Brasil posee un sólido marco jurídico ambiental, la ausencia de una gran estrategia nacional que integre seguridad, desarrollo y la cuestión climática puede volver vulnerable al Estado brasileño frente a la instrumentalización ambiental por parte de potencias extranjeras. Se concluye, por lo tanto, que es necesario reforzar políticas públicas sostenibles y estrategias de defensa que incorporen la variable climática, todas incluidas en una gran estrategia nacional que otorgue sinergia al proceso.

Palabras clave: securitización; geopolítica ambiental; sostenibilidad estratégica; soberanía; gran estrategia.

Résumé
Cet article analyse le lien croissant entre la question climatique et les domaines de la sécurité et de la défense, avec un accent particulier sur la région amazonienne. Il part de la reconnaissance que l'environnement naturel, en particulier l'Amazonie, est devenu un élément central des disputes géopolitiques contemporaines. L'objectif est d'examiner comment la crise climatique peut être sécuritisée, se transformant en instrument de pression internationale et en risque pour la souveraineté nationale. La recherche adopte une approche qualitative, avec une revue de la littérature et une analyse documentaire des cadres stratégiques et normatifs. Les résultats indiquent que, bien que le Brésil dispose d'un cadre juridique environnemental robuste, l'absence d'une grande stratégie nationale intégrant la sécurité, le développement et la

question climatique peut rendre l'État brésilien vulnérable à l'instrumentalisation environnementale par des puissances étrangères. Il en résulte qu'il est nécessaire de renforcer les politiques publiques durables et les stratégies de défense intégrant la variable climatique, toutes incluses dans une grande stratégie nationale qui confère une synergie au processus.

Mots-clés: sécuritisation; géopolitique environnementale; durabilité stratégique; souveraineté; grande stratégie.

1 INTRODUCTION

The climate issue emerges as one of the greatest challenges of the 21st century, given that its implications go beyond the limits of ecology and penetrate the fields of geopolitics, economics, international security, and national defense. Amazonia, due to its complex reality, plays a prominent role in this debate. Its territory, shared by nine countries, including Brazil, can be the object of symbolic and material disputes involving state and non-state actors, mobilizing environmental, economic, and strategic interests.

In this scenario, the prominence of environmental issues as a vector for reconfiguring power relations in the international system is growing. The Brazilian Amazonia is, at the same time, a national environmental asset and a sensitive geopolitical space, whose governance raises concerns about sovereignty, security, and sustainable development. The increasing visibility of the region generates external pressures that, under the guise of environmental preservation, can take on the contours of political, economic, and normative interference.

This article, therefore, focuses on the following problem: to what extent can the climate issue represent a threat to Brazilian sovereignty in the Amazonia, based on the logic of securitization proposed by the Copenhagen School?

As hypotheses, it is considered that (i) the international environmental agenda has been used as an instrument of symbolic and economic coercion by central powers; and (ii) Brazil's vulnerability increases in the absence of a Grand Strategy, conceived here as the integrated and long-term arrangement that guides national goals and articulates sectoral means and policies, which incorporates climate security in a cross-cutting manner.

The overall objective of this work is to analyze the implications of the climate issue for security and defense in the Amazon region, in the present and future, from the perspective of the Copenhagen School. As specific objectives, it intends to present the theoretical foundations of securitization; discuss the specificities of the Amazonia and the environmental and strategic challenges that surround it; and examine the contemporary mechanisms of cooperation and domination associated with the climate agenda.

In this way, the article proves relevant in its proposal to articulate the environmental debate with international security studies, in order to contribute to a critical understanding of the dynamics that pressure national sovereignty in the name of sustainability. In addition, it seeks to offer input for the formulation of public policies consistent with Brazilian strategic interests.

Methodologically, a qualitative approach is adopted with systematic bibliographic and documentary analysis. The empirical corpus is composed of national strategic documents (National Defense Policy - PND, National Defense Strategy - END, Brazilian Defense White Paper - LBDN), international treaties and agreements on environment and security, reports from the Amazon Cooperation Treaty Organization (ACTO), and resolutions from climate conferences (COPs). Selection criteria included: (i) centrality to security, climate, and the Amazon, (ii) source authority, and (iii) accessibility and completeness. The analysis technique employed was the securitization matrix triangulated with theoretical literature, and the procedure involved independent double reading, thematic coding, and analytical synthesis to integrate theory and evidence.

The article is structured in four sections, in addition to this introduction. The first section presents the theoretical foundations of the Copenhagen School, highlighting the concept of securitization. The second section addresses the Amazonia as a strategic space in the face of climate change. The third analyzes the relationship between international cooperation and domination, in light of the climate issue. The fourth discusses the impacts of the environmental agenda on national security and defense policies. Foresight principles are included throughout the sections. Finally, in the concluding remarks, the ideas discussed are summarized and future perspectives are outlined.

2 COPENHAGEN SCHOOL AND COMPREHENSIVE SECURITY

Following the end of the Cold War, changes occurred that catalyzed transformations in how international security came to be understood. That is, with the decline of the bipolar order, a theoretical framework was constructed to seek alternatives to the idea of what should be understood as security, shifting the view that external military threats are the only ones to be considered a danger to a State.

At this point, it is worth mentioning how environmentalism was incorporated into security studies. The pioneering work was done by Lester Brown (1977), with the publication of *Redefining National Security*. Following this, Richard Ullman published *Redefining Security*

in 1983. The catalytic role of the Brundtland Report, which advocated for broadening the scope of the concept of security to encompass the potential deleterious effects of environmental degradation, should also be considered (COMISSÃO MUNDIAL SOBRE MEIO AMBIENTE E DESENVOLVIMENTO – CMMAD, 1991, p. 21).

Within this context, the Copenhagen School emerged, formed by authors such as Barry Buzan, Ole Wæver, and Jaap de Wilde, which proposed a reconfiguration of the concept of security through the theory of securitization, articulating the idea of comprehensive security, incorporating threats of a political, economic, societal, and environmental nature. This theory is based on the principle that security is not merely an objective condition, but a political-discursive act by which a securitizing actor identifies an existential threat to a referential object, seeking to convince an audience of the need to adopt exceptional measures to neutralize it.

Dos Santos (2021, p. 13) points out that "the Copenhagen School, by proposing the progressive incorporation of new themes and actors in security studies, based on its own conceptual framework, broadened the fields of analysis, justifying the comprehensive name by which it became known."[1]

According to Buzan, Wæver, and Wilde (1998, p. 23), security is “the move that takes politics beyond the established rules of the game and frames the issue either as a special kind of politics or as above politics.” Thus, the securitization process comprises three main stages: (i) Non-politicized, when the issue is not the subject of public debate or relevant government action; (ii) Politicized, it enters the public agenda and is addressed within the framework of ordinary policies and institutions, with resource allocation and the formulation of norms; and (iii) Securitized, it is constructed as an existential threat that demands extraordinary actions.

This movement is initiated by a securitizing actor and validated by an audience, characterizing itself as an intersubjective process. Thus, a topic can move from a "non-politicized" to a "politicized" state and, finally, be securitized, that is, treated as an existential threat that justifies actions outside the ordinary political norm. The ideal result, according to the authors, is desecuritization, when a topic returns to treatment within the ordinary political sphere (Buzan; Wæver; de Wilde, 1998, p. 29).

It is noted that the structure proposed by the Copenhagen School allows for an understanding of the instrumentalization of themes such as security, with particular emphasis on the climate issue. Climate change, due to its cross-cutting impact – affecting water resources,

[1] Free translation by the translator from the original: “a Escola de Copenhague ao propor a incorporação progressiva de novos temas e atores nos estudos de segurança, com base numa estrutura conceitual própria ampliou os campos de análise, justificando a denominação abrangente como ficou conhecida”.

biodiversity, public health, agriculture, infrastructure, and social stability – is becoming increasingly susceptible to securitization by state and non-state actors.

Dos Santos (2021, p. 14) explains that:

> The securitization theory proposed by the Copenhagen School embodies an intersubjective process in which the problem is presented as a threat to the existence of a given referential object, requiring exceptional and emergency measures to solve it. These measures or actions are sometimes outside the conventional limits of customary political praxis.[2]

In this scenario, the risk emerges that environmental discourse will be manipulated as an instrument of international coercion, transforming the climate issue into a vector of geopolitical power. As Buzan, Wæver, and Wilde (1998) observe that two problems stand out in this sector: firstly, environmental threats are mostly unintentional; and secondly, there is still great uncertainty about what kind of political structures environmental issues will produce.

At this point, it is worth highlighting that high levels of uncertainty and risk are factors that point to the need for the use of prospective scenarios, within the set of strategic planning tools, for the construction of robust and resilient public policies that allow decision-makers to mitigate risks and reduce the degree of future uncertainties.

As a consolidated instrument within the scope of management, strategic planning has, among its tools, the construction of prospective scenarios, which consists of projecting different future possibilities based on critical variables (Marcial; Grumbach, 2008, p. 12).

Therefore, the effects of environmental securitization are visible in practices such as the imposition of environmental tariff barriers and trade restrictions based on ecological standards. The use of legal and media mechanisms by central powers and coalitions of international actors can represent a subtle way of subjecting the sovereignty of developing countries, such as Brazil, to the normative logic of foreign interests disguised as environmental defense.

It is important to emphasize that, for Buzan; Wæver; Wilde (1998, p. 31), the concept of threat is not an objective reality in itself, but an intersubjective construction: it is the shared acceptance between actor and audience that legitimizes the classification of something as an existential threat. In the climate field, this means that external pressures only translate into effective securitization when there is discourse accepted as such.

It is understood that the concept requires the intentionality of an actor and acceptance by the audience, which means that the climate threat only becomes a securitized threat if there is a successful discourse in this regard. The growing international attention on the Pan-Amazon,

[2] Free translation by the translator.

for example, can be read as part of an attempt to construct a discursive global threat, with implications that go beyond the environmental field and touch on sovereignty.

Consequently, it is possible to observe that, among the existing scenarios within securitization, lies the challenge of responding to climate change without allowing it to be used as a pretext for the erosion of national sovereignty. The absence of a robust Grand National Strategy that integrates climate security increases Brazil's vulnerability to external securitization, resulting in a possible difficulty in building its own environmental agenda, balancing environmental protection and economic development.

For conceptual purposes, the Grand National Strategy transcends the strictly geopolitical sphere and also assumes a constitutional dimension. In the context of the Democratic Rule of Law, the Constitution establishes the parameters that guide the strategic actions of the Brazilian State, while the Grand Strategy acts as an instrument for realizing the fundamental objectives enshrined in Article 3, paragraphs I to IV, of the Federal Constitution (Góes, 2024, pp. 35-36).

In summary, the Copenhagen School approach provides an analytical foundation for understanding how political processes involve the emergence of climate crisis and can result in global tension. As explained, this approach broadens the view of security beyond the military dimension, allowing us to understand how discourses shape international practices and directly affect the capacity for self-determination of states in environmentally sensitive regions such as the Amazonia.

Therefore, the complexity involved in climate issues is evident, highlighting that, to address such a relevant topic, experts point to the viability of using strategic planning techniques and tools that allow decision-makers to guide their activities with flexibility.

According to Porter (1989), scenarios can be perceived as a set of plausible hypotheses about the uncertainties that may influence the prospecting object, with a consistent view of future reality. Using Porter's own words (1989, p. 15), we have the concept that “scenarios are an internally consistent view of future reality, based on a set of plausible assumptions about the uncertainties that may influence the prospecting object.”[3]

Thus, the use of prospective scenarios is suggested in order to visualize new possibilities and routes. This confirms the need to use tools for analyzing future reality, lending quality to the planning of public policies.

[3]Free translation by the translator.

Understanding that there may be an increase in pressure from international groups and central powers, whether through attempts to impose international norms on Brazilian territory or through the difficulty in managing interests in sensitive regions, it is also necessary to align issues related to the Amazon, which is done below.

3 AMAZONIA AND THE CLIMATE ISSUE

The Pan-Amazon region is recognized as the largest tropical biome in the world, encompassing nine South American countries. In Brazil, the area corresponding to the Legal Amazon extends over approximately 6.9 million km², representing 58.93% of the national territory (INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA – IBGE, 2023, p. 65; ORGANIZAÇÃO DO TRATADO DE COOPERAÇÃO AMAZÔNICA – OTCA, 2017, p. 2).

When the approach is from a regional perspective, it becomes known as Pan-Amazon and extends across the territory of Venezuela, Peru, Bolivia, Colombia, Ecuador, Guyana, and Suriname, as well as the overseas territory of French Guiana. This transnational dimension reinforces the need for coordinated policies that, within the logic of securitization, function as endogenous responses favorable to the defense of the Amazon, and that refute the existential threat contained in international discourse.

Figure 1 – Pan-Amazon Map

Source: Costa (2020).

This expanse is equivalent to the largest continuous tropical forest on the planet and includes not only the dense equatorial forest, but also transition areas to other South American

biomes, forming a complex ecological and hydrological network (OTCA, 2017, p. 23). In this sense, international discourses that link global climate balance to Amazonian preservation can function as securitization acts, shifting the debate from the political plane to one of existential urgency.

From Sachs's (2008) perspective, the future of humanity will depend on the fate of the Amazon rainforest. Far from being the "Garden of Eden" or the "green hell" portrayed by extreme views, the Amazon demands recognition beyond its ecological and strategic importance, in order to incorporate environmental preservation into development policies that reconcile the sustainable exploitation of its resources with the maintenance of the sovereignty of the countries that share it.

Although common, describing the Amazon as the "lungs of the world" is a scientific misconception. The popular metaphor misinforms by suggesting the Amazon as the planet's main supplier of oxygen (Oliveira, 1991), illustrating how environmental narratives, even if flawed, can be mobilized to influence perceptions and justify interventions, highlighting the discursive dimension of securitization. In reality, its net contribution to global oxygen production is practically nil, as the oxygen released is consumed by respiration and biomass decomposition, requiring a critical review of this environmental rhetoric.

Although the importance of the Amazon is recognized, there is a notable lack of international consensus on appropriate measures for its preservation. The approaches proposed at the Conferences of the Parties (COPs) on climate change, such as COP 21 in Paris (2015), COP 3 in Kyoto (1997), COP 26 in Glasgow (2021), and COP 28 in Dubai (2023), reveal the disparity between the expectations of developed countries and the interests of Amazonian countries. This scenario reveals the politicized stage of the Amazonian issue: the topic is on the public and institutional agenda, mobilizing resources and decisions, but without any legitimized exceptional actions that would characterize full securitization.

Therefore, it is understood that, when compared to other regions of the country, the Amazon may present peculiarities, such as geographic isolation and the need for specific public policies for development that is responsive to the environment. Dos Santos (2021, p. 42) makes an important point that the debates surrounding the Amazon are intrinsically connected to other terms:

> Discussions about the Amazon are interwoven with other related terms such as borders, environment, indigenous peoples, traditional populations, economic exploitation, sovereignty, scarcity of natural resources, forest, water, biodiversity, preservation, sustainable development, and others. From this perspective, and beyond regional geographic determinism, the conceptual dimensions of these terms point to the need for complex and comprehensive

> solutions, which must be agreed upon multilaterally by all Amazonian stakeholders.[4]

This tension manifests itself in proposals that, although cloaked in environmental rhetoric, can serve as instruments of diplomatic and economic coercion. A prime example is the Triple A Corridor project (Andes-Amazon-Atlantic), proposed by the Colombian government and supported by other international actors. The initiative aimed to create a continuous ecological corridor between the Andes and the Atlantic, crossing strategic territories.

However, it was harshly criticized by Brazilian authorities, especially in the defense sector, who pointed to the absence of bilateral dialogue and the risk of international interference under the pretext of environmental preservation (Dos Santos, 2021). The Brazilian reaction highlights how the Amazon can become a field of geopolitical disputes disguised as ecological concerns.

Furthermore, the complexity of the Amazonian biome goes beyond its ecological dimension. It is a region marked by socioeconomic inequalities, a chronic lack of infrastructure, a shortage of public services, and logistical difficulties. These characteristics hinder the implementation of effective and sustainable environmental policies. As Bezerra (2013, p. 170) points out, the development of the Amazon demonstrates a possibility of economic development in harmony with local particularities, that is, an approach that articulates sovereignty, regional cooperation, and a minimum infrastructure of connectivity.

The region's internal weaknesses make it even more vulnerable to external pressures. The lack of unity of thought at the international level regarding preservation criteria and unilateral initiatives reinforce the need for a well-defined Brazilian strategic position. This can be seen in the increasing use of environmental tariff barriers by developed countries, such as the requirement for green certifications for agricultural imports, which exemplifies how the climate agenda can be used as an instrument of economic domination (Ribas; Riet, 2025, p. 130).

At this stage, the focus is on future possibilities and risks arising from the conduct of the Brazilian State and the actions of other actors that may not align with Brazilian interests for the future of the region

Ribas, Dos Santos, and Konno (2025, p. 303) explain that "projecting the future differs from prospecting the future." The former seeks historical series and short-term data;

[4] Free translation by the translator.

prospecting, on the other hand, is directed towards the medium and long term, in order to identify megatrends and possible disruptions. Therefore, scenarios must be constructed in strategic planning to minimize uncertainties within a pre-established time horizon.

Thus, it becomes clear how imperative the use of prospective scenarios is in supporting the strategic planning of the Amazon region in order to promote the robustness, flexibility, and resilience of future public policies for that region.

In short, the Amazon should be understood not only as an environmental asset, but as a strategic territory whose preservation requires sovereign environmental governance, based on cooperation among stakeholders. It therefore demands coordinated endogenous actions that reconcile conservation, development, and sovereignty, neutralizing attempts at exogenous securitization and reinforcing the leading role of the Amazonian states.

4 CLIMATE ISSUE, COOPERATION AND DOMINATION

International concern for the environment gained momentum starting in the 1960s, driven by climatic events such as the emergence of acid rain, the destruction of the ozone layer, and the recognition of the greenhouse effect as a global phenomenon caused primarily by human activities.

In the United States of America, the publication of Rachel Carson's book *Silent Spring* (1962) stands out as a symbolic milestone in the environmental awakening. It denounced the impacts of dichlorodiphenyltrichloroethane (DDT), an insecticide widely used at the time, on ecosystems, becoming a reference point for the modern environmental movement.

Since then, environmental issues have become increasingly important topics in international forums, especially after the Stockholm Conference (1972) and the publication of *The Limits to Growth* by the Club of Rome, which projected catastrophic scenarios if the model of unchecked economic growth persisted (Lago, 2013, p. 24). These initiatives anticipated the contemporary debate on the planet's limits and the costs of development. However, they also revealed a central tension: who will bear the costs of ecological transitions? Which countries will be able to impose their paradigms of environmental preservation?

The Copenhagen School's theory of securitization offers a lens through which to understand how this debate can be instrumentalized. According to Buzan and Hansen (2009, p. 214), security "does something" (securitizes) by framing an issue as an existential threat. In the environmental sector, this framing allows for the legitimization of exceptional measures, including sanctions and trade restrictions, as a way to pressure states to adopt specific policies.

Therefore, the discourse of security not only describes a threat, but produces that threat by naming it as such, legitimizing exceptional actions that deviate from the normal course of politics. Securitizing actors, such as political leaders or international institutions, can present environmental destruction as an existential threat, justifying extraordinary measures such as sanctions, trade barriers, or diplomatic interference.

In the case of the Amazon, this logic manifests itself when international actors present the forest as a global reference point and question Brazil's ability to preserve it, shifting the issue to a level where sovereign decisions can be relativized in the name of "planetary survival."

Brazil, however, has a robust environmental legal framework. The 1988 Federal Constitution enshrined environmental protection as a fundamental right (Article 225), establishing robust policies such as the Forest Code (Law No. 12,651, of May 25, 2012), the National Environmental Policy (Law No. 6,938, of August 31, 1981), and control mechanisms such as the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) and the National System of Conservation Units (SNUC).

However, the existence of these norms does not prevent the country from being the target of securitization narratives, since securitization is less about objective capabilities and more about discursive constructions accepted by an international audience. At the international level, the effects of climate change are felt unevenly. Most greenhouse gas emissions are generated by a limited number of industrialized countries, while the environmental impacts fall disproportionately on developing nations (Giddens, 2010, p. 268).

Climate conferences, such as Kyoto (1997), Paris (2015) and Glasgow (2021), show that developed countries tend to defend stricter regulatory standards, while developing countries emphasize the right to growth and climate justice. This divergence fuels a politicized scenario, in which the environmental agenda is negotiated politically, but it still does not justify, in the Brazilian case, exceptional actions that would characterize full securitization.

The case of the Arctic exemplifies this logic: with the melting of polar ice, powers such as the United States, Russia, China, and Canada began to compete for maritime routes and the natural resources available there, prioritizing strategic and economic interests even in the face of ecological warnings. The prevalence of geopolitics over ecopolitics reveals how the environmental agenda can be relativized in the face of national interests, reinforcing the thesis that the discourse of preservation can serve as a pretext for practices of domination (Viola; Franchini, 2012).

The imposition of sustainable standards disconnected from local socioeconomic realities exemplifies this trend, simultaneously delegitimizing sovereign environmental

management policies compatible with the development interests of peripheral countries. Thus, under the guise of environmental preservation, a new form of discursive colonialism is constructed, in which ecology serves as a vector of power and international influence.

In the case of the Amazon, the ecosystem is frequently constructed as a global reference point, opening the way for the relativization of the sovereignty of Amazonian countries. Such discourse, even if disguised as environmental concern, can mask geopolitical disputes over strategic resources, such as water, minerals, and biodiversity, and connects to Viola and Franchini's (2012) critique of the political use of ecopolitics as a pretext for practices of domination.

Environmental security also reflects epistemic and material disputes between the Global North and South. As Buzan and Hansen (2009, p. 129) point out, the first studies on environmental degradation emerged "within overlapping scientific and policy agendas," that is, from technical-normative agendas that tended to preserve the perspective of the central countries.

However, critical approaches – such as Postcolonial Studies, Peace Research, and Human Security – highlight that the impacts of environmental degradation fall disproportionately on peripheral countries, even though these have historically contributed less intensely to emissions. This asymmetry is visible in climate conferences, where developed countries push for regulatory commitments that often limit the possibilities for economic growth in developing countries, creating new forms of environmental subordination.

It can be seen that the imposition of environmental restrictions can, therefore, become a tool of economic and diplomatic domination, through mechanisms such as environmental tariff barriers, conditionalities for international financing, and asymmetrical trade agreements. The Amazon is part of this global landscape of dispute.

With its vast biodiversity and sources of strategic resources, the biome becomes the target of external pressures, including in the form of securitization narratives. According to Antiquera (2006, p. 19), the growing global attention to the Amazon due to its ecological relevance raises the alarm among Amazonian countries about possible attempts to relativize their sovereignties. As Santos (2018, p. 105) warns, the scarcity of natural resources and environmental vulnerability increase the risk of external securitization over the Amazonian territory.

The climate issue emerges, therefore, as an arena of necessary cooperation, but also as a potential field of domination. The challenge lies in building a balance between the objectives of environmental preservation and the rights to sovereign development. This reconciliation

requires a leading role for the state, active environmental diplomacy, and public policies that integrate sustainability and strategic autonomy.

5 SEGURITY, DEFENSE AND ENVIRONMENT

The growing visibility of the climate issue on the international stage has increased the importance of its articulation with the security and defense sectors. In an increasingly interdependent world, environmental guidelines have come to be used as mechanisms for international insertion and credibility. For Brazil, a country with a vast territory and immense biodiversity, especially in the Amazon region, this implies aligning its public policies with international norms without relinquishing sovereignty and national strategic interests.

They must also consider the so-called "deep forces" (Duroselle, 2000, p. 186), which are geographical, demographic, economic, cultural, and sentimental structural conditions that shape the perception and response of States. These factors influence the context in which securitizing speech acts about the Amazon gain traction, increasing receptiveness to narratives that seek to shift the issue to the securitized stage or maintain its management within the politicized sphere.

Environmental security, in this context, goes beyond the simple preservation of ecosystems: it becomes a fundamental variable for political, energy, food, and water stability. Prospective scenarios, such as *Brazil 2035* by Ipea and Assecor (Marcial *et al.*, 2017, p. 191), indicate that the Amazon will continue to be a focus of tension, both due to the strategic value of its resources and the international pressures seeking to influence its environmental governance.

Climate threats, therefore, do not act in isolation. They tend to catalyze or exacerbate existing threats, such as migration crises, border tensions, and disputes over energy resources. As Krausmann *et al.* (2009, p. 14) argue, the increase in global demand and per capita consumption imposes significant pressures on the extraction and use of resources, intensifying the risks of instability.

In this scenario, the centrality of the State as an agent of security is reaffirmed. Despite contemporary criticisms of the State's capacity, it is the State that holds the legitimate monopoly on the use of force and the responsibility for guaranteeing territorial integrity and the well-being of its population (Ferrajoli, 2002, p. 48). Sovereignty, in this sense, constitutes a non-negotiable pillar for the definition of environmental and defense policies.

Environmental security, in this context, must be incorporated as a strategic variable in the formulation of a Grand Strategy. In the Brazilian case, the National Defense Policy (PND), the National Defense Strategy (END), and the Brazilian Defense White Paper (LBDN) form the instrumental core. In light of securitization theory, this arrangement delineates when environmental risks remain in the politicized stage (ordinary management) and when they demand exceptional measures of defense, sustainable development, or resilience in the face of external pressures.

However, from a securitization perspective, these documents remain predominantly in the politicization stage: they acknowledge strategic relevance, but do not establish mechanisms that integrate the climate goals of the National Plan on Climate Change (PNMC) with defense actions, nor measures that characterize a fully securitized response, which reinforces institutional fragmentation and the difficulty of translating rhetoric into practice.

The PND, nevertheless, establishes a formal link between the environment and security, which allows us to infer that the Brazilian State admits the possibility of securitizing the environmental sector. This provision aligns with the logic of environmental securitization by recognizing that climate and environmental threats can be framed as risks to national security. In section 2 of the PND, entitled "The context of the National Defense Policy," item 2.3.5 states the following:

> (...) the global expansion of human activities, resulting from economic and population growth, has led to an increased demand for natural resources. Therefore, the intensification of disputes over maritime areas, spatial dominance, and sources of fresh water, food, mineral resources, biodiversity, and energy cannot be ignored. Such issues may lead to interference in internal affairs or controversies over interests in spaces subject to state sovereignty, creating potential conflict scenarios[5] (Brasil, 2020, p. 17).

Beyond the Brazilian case, international experiences indicate the growing incorporation of the environmental agenda into defense structures. The European Union, for example, announced in 2021 the creation of an environmental protection force within its security and defense policy, aimed at actions in areas vulnerable to climate disasters and ecological conflicts. Such initiatives exemplify the politicized or even securitized phase of the environmental agenda in certain contexts, according to the Copenhagen School.

Amazonian geopolitics, therefore, needs to be understood as a space of symbolic and material dispute. Meira Mattos (2005) already warned of the need for integration of the national

[5] Free translation by the translator.

territory through the strategic occupation of borders, aiming at protection against the internationalization of the Amazon and the preservation of its natural resources.

In the same vein, Bertha Becker (2005) warns of the transformation of contemporary geopolitics, which acts diffusely on the decisions of States, using unconventional instruments to influence the use and control of territories.

> Geopolitics has always been characterized by the presence of pressures of all kinds, interventions in the international arena ranging from the mildest to wars and territorial conquests. Initially, these actions had the State as their fundamental subject, as it was understood as the sole source of power, the only representation of politics, and disputes were analyzed only between States. Today, geopolitics acts, above all, through the power to influence the decision-making of States regarding the use of territory, since the conquest of territories and colonies have become very expensive. Thus, the vast geographical areas delimited by multinational borders, as well as a very rich patrimony to be explored together with its Amazonian partners, evoke international threats and covetousness over the region.[6]

The integration of the Amazon as an object of international security must be analyzed in light of Critical Security Studies, especially the theory of securitization. For Buzan and Hansen (2009, p. 214), securitization means shifting a topic from the field of ordinary politics to that of urgency, legitimizing exceptional actions.

In this context, the Amazon is not merely a tropical forest, but a referential object whose protection has been invoked in international discourses that, while calling for environmental preservation, may relativize the sovereignty of the Pan-Amazonian States. The Amazon Cooperation Treaty Organization (ACTO), created with the objective of strengthening regional cooperation and protecting the territorial integrity of the Amazonian countries, represents a multilateral institutional response to these securitizing narratives (Dos Santos; Ribas, 2024, p. 17).

The actions of the ACTO reveal that multilateralism among Amazonian countries can function as endogenous securitization strategies, in which the Amazonian states themselves recognize risks and formulate joint responses, reinforcing autonomy in the face of external pressures. This post-hegemonic model is relevant to the Global South, as it integrates environmental cooperation and the defense of sovereignty. According to Santos and Ribas (2024, p. 20), the creation of the organization aimed to react to subliminal discourses that relativized Brazilian sovereignty and sought to build a cohesive diplomatic front against the internationalization of the biome.

[6] Free translation by the translator.

This arrangement demonstrates that the Pan-Amazonian countries recognize the importance of environmental cooperation but reject any attempt at geopolitical subordination in the name of ecology. The ACTO, therefore, embodies a model of endogenous securitization – not as an imposition from the outside in, but as a collective action in defense of sovereignty, environmental preservation, and regional sustainability. The articulation between sovereignty and environmental security, in this sense, takes on distinct contours in the Global South. While in central countries environmental security tends to be understood as a technical-normative imperative with a universalizing vocation, in the geopolitical peripheries it is intertwined with the affirmation of autonomy and resistance to dependence.

Buzan and Hansen (2009, p. 129) draw attention to the tendency of traditional approaches to environmental security to maintain the State as a referential object, but to ignore structural inequalities in the international system. The ATCO, on the other hand, emerges as an example of a post-hegemonic environmental security initiative: anchored in regional experiences, geared towards emancipation, and founded on cooperation among equals.

Given this, it becomes essential to build defense policies that articulate sovereignty, development, protection, and environmental defense. The complexity of contemporary challenges demands strategic planning based on prospective scenarios, broad inter-institutional dialogue, and the valorization of the Amazon as a national asset, whose defense is an inseparable part of the country's project.

The growing global interdependence and transnational environmental challenges have brought to light a structural tension between the paradigms of sovereignty and environmental security. While the former are based on the principle of self-determination of peoples and non-intervention (Dallari, 1981, p. 109), the latter demands international coordination, binding commitments, and often partial renunciation of the exclusive decision-making authority of States. For Amazonian countries, this dilemma is particularly acute: how to cooperate internationally without relinquishing control over their territories, turning to national development?

The ACTO offers a unique model for overcoming this dichotomy. By articulating sovereignty and multilateralism among countries that share the same ecosystem, it allows environmental governance to be exercised with legitimacy and territorial knowledge. As Dos Santos, Ribas, and Konno (2023, p. 13) emphasize, globalization has caused selective erosions of sovereignty, mainly affecting peripheral countries; in this context, the ACTO functions as a counter-hegemonic instrument, allowing regional solutions to global problems. This

arrangement reinforces the idea that sovereignty should not be seen as an obstacle to cooperation, but as a condition for fair and equitable environmental governance.

This perspective contrasts with that of sectors in the Global North, which frequently advocate forms of "global environmental governance" that, in practice, operate as mechanisms of surveillance and conditioning. Thus, an emancipated environmental security – as proposed by critical studies – needs to be rooted in regional arrangements such as the ACTO, which reconcile environmental protection with sovereignty and distributive justice among peoples.

6 CONCLUDING REMARKS

The rise of the climate issue on the agenda of the international system has transformed the way states, multilateral organizations, and other actors approach defense and security issues. Far from being restricted to the environmental sphere, the climate crisis has become a cross-cutting vector of geopolitical disputes, especially in regions with high ecological and strategic relevance, such as the Amazonia.

In this scenario, Brazil occupies an ambivalent position: it is a normative protagonist in global environmental forums, but also the target of securitizing narratives that call into question its sovereignty over the Amazon. The analysis developed demonstrated that, according to the Copenhagen School, this framing is neither neutral nor strictly technical, but the result of political and discursive processes that intersubjectively construct the Amazon as a referential object of international security, justifying potential normative, diplomatic, and economic interventions.

The ACTO study demonstrated that the pan-Amazonian countries have resisted this verticalized logic through a cooperative, horizontal, and multilateral approach. This initiative can be interpreted, sometimes as cooperative coordination at the politicized stage and, in certain aspects, as a desecuritization strategy, by bringing the issue into ordinary governance among the Amazonian states, without triggering exceptional measures.

At the same time, international environmental governance instruments, such as climate treaties and "green" trade mechanisms, can operate as tools of normative domination when they do not incorporate climate justice and respect for the autonomy of states. This risk requires Brazil to act as a rule-maker and not just as a recipient, challenging frameworks that threaten its sovereignty.

The country has one of the most robust environmental legal frameworks in the world, which gives it the normative capacity to lead the sustainable development agenda. However,

this normative strength needs to be integrated into a Grand Strategy that incorporates the climate variable across defense, security, infrastructure, diplomacy, development, and innovation policies. Without this integration, Amazonia will remain vulnerable to external pressures that instrumentalize the environmental agenda as a mechanism of coercion.

The defense of Amazonia is not limited to containing external threats but also requires the construction of internal conditions for its sustainable, integrated, and secure development, with a strengthened state presence, investments in science and technology, sustainable infrastructure, and participatory governance mechanisms. The tension between environmental security and sovereignty is structural, manifesting itself, for example, in the COPs, where developed countries defend strict regulatory commitments, while developing countries demand climate justice and compensation for historical inequalities.

This asymmetry reveals how the climate agenda can operate as an instrument of normative coercion and diplomatic domination, especially when linked to tariff barriers, trade restrictions, or financial conditionalities. In this context, the strengthening of regional arrangements such as the ACTO emerges as a counter-hegemonic alternative, capable of articulating a South American vision of environmental security and restoring decisional autonomy on issues central to national and regional security.

Amazonia is simultaneously a challenge and an opportunity: a challenge due to its geopolitical and socio-environmental vulnerability; an opportunity due to its centrality in the construction of a civilizational paradigm based on cooperation, diversity, and regional integration. The future of Brazilian environmental security will depend, to a large extent, on the ability to combine sovereignty, multilateralism, and sustainable development within the same strategic horizon.

Recognizing the Amazonia as a geopolitical asset, and not just as an environmental liability, is a sure step to ensure that Brazil remains an active subject in the formulation of its own climate, development, security, and defense agenda. Therefore, the reflection proposed here points to the repositioning of the climate issue as a strategic security theme for the Brazilian State. This does not imply automatic militarization, but rather its recognition as a vector for public policies, defense strategies, international agreements, and development programs harmonized under the logic of sovereign sustainability.

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Half a century of air temperature changes in the capitals of the Legal Amazon

Meio século de mudanças na temperatura do ar nas capitais da Amazônia Legal

Medio siglo de cambios en la temperatura del aire en las capitales de la Amazonía Legal

Un demi-siècle de changements de température de l'air dans les capitales de l'Amazonie légale

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Abstract

Rising temperatures have a significant impact on urban centers in the Amazon. This study aimed to analyze the temporal evolution and warming trends of air temperature in the capitals of the Legal Amazon over the last half century (1970-2024), with an emphasis on identifying warming trends. ERA5 reanalysis data were used, applying the Mann-Kendall test, Sen estimator, and Pettitt test to identify trends and change points. All capitals showed statistically significant warming trends (Z_{MK} 5.78 to 7.23, p<0.0001), with annual increase rates ranging from 0.019°C to 0.032°C. Change points were predominantly identified between the 1990s and 2000s.

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Comparison between pre- and post-change periods revealed significant temperature increases, with amplitudes between 0.52°C (São Luís) and 0.91°C (Boa Vista), indicating substantial warming and spatial heterogeneity, with greater intensity in the north of the region and in transition zones. The study provides robust evidence of persistent warming in Amazonian capitals, contributing crucial data for climate adaptation policies and urban planning in this sensitive region.

Keywords: Legal Amazon; climate change; urban warming.

Resumo

O aumento das temperaturas impacta significativamente os centros urbanos da Amazônia. Este estudo teve como objetivo analisar a evolução temporal e as tendências de aquecimento da temperatura do ar nas capitais da Amazônia Legal no último meio século (1970-2024), com ênfase na identificação de tendências de aquecimento. Utilizaram-se dados de reanálise ERA5, aplicando os testes de Mann-Kendall, estimador de Sen e teste de Pettitt para identificar tendências e pontos de mudança. Todas as capitais apresentaram tendências de aquecimento estatisticamente significativas (Z_{MK} 5,78 a 7,23, p<0,0001), com taxas de aumento anual variando de 0,019°C a 0,032°C. Pontos de mudança foram predominantemente identificados entre as décadas de 1990 e 2000. A comparação entre os períodos pré e pós-mudança revelou aumentos significativos de temperatura, com amplitudes entre 0,52°C (São Luís) e 0,91°C (Boa Vista), indicando aquecimento substancial e heterogeneidade espacial, com maior intensidade no norte da região e em zonas de transição. O estudo fornece evidências robustas do aquecimento persistente nas capitais amazônicas, contribuindo com dados cruciais para políticas de adaptação climática e planejamento urbano nesta região sensível.

Palavras-chave: Amazônia Legal; mudanças climáticas; aquecimento urbano.

Resumen

El aumento de las temperaturas impacta significativamente los centros urbanos de la Amazonía. Este estudio tuvo como objetivo analizar la evolución temporal y las tendencias de calentamiento de la temperatura del aire en las capitales de la Amazonía Legal en el último medio siglo (1970-2024), con énfasis en la identificación de tendencias de calentamiento. Se utilizaron datos de reanálisis ERA5, aplicando las pruebas de Mann-Kendall, el estimador de Sen y la prueba de Pettitt para identificar tendencias y puntos de cambio. Todas las capitales presentaron tendencias de calentamiento estadísticamente significativas (Z_MK 5,78 a 7,23, p<0,0001), con tasas de aumento anual que varían entre 0,019°C y 0,032°C. Los puntos de cambio fueron predominantemente identificados entre las décadas de 1990 y 2000. La comparación entre los períodos pre y post-cambio reveló aumentos significativos de temperatura, con amplitudes entre 0,52°C (São Luís) y 0,91°C (Boa Vista), lo que indica un calentamiento sustancial y

heterogeneidad espacial, con mayor intensidad en el norte de la región y en zonas de transición. El estudio proporciona pruebas sólidas del calentamiento persistente en las capitales amazónicas, contribuyendo con datos cruciales para políticas de adaptación climática y planificación urbana en esta región sensible.

Palabras clave: Amazonía Legal; cambio climático; calentamiento urbano.

Résumé
L'augmentation des températures impacte de manière significative les centres urbains de l'Amazonie. Cette étude visait à analyser l'évolution temporelle et les tendances de réchauffement de la température de l'air dans les capitales de l'Amazonie légale au cours du dernier demi-siècle (1970-2024), en mettant l'accent sur l'identification des tendances de réchauffement. Des données de réanalyse ERA5 ont été utilisées, en appliquant les tests de Mann-Kendall, l'estimateur de Sen et le test de Pettitt pour identifier les tendances et les points de changement. Toutes les capitales ont montré des tendances de réchauffement statistiquement significatives (Z_MK 5,78 à 7,23, p<0,0001), avec des taux d'augmentation annuels variant de 0,019°C à 0,032°C. Les points de changement ont été principalement identifiés entre les décennies de 1990 et 2000. La comparaison entre les périodes avant et après le changement a révélé des augmentations significatives de température, avec des amplitudes allant de 0,52°C (São Luís) à 0,91°C (Boa Vista), indiquant un réchauffement substantiel et une hétérogénéité spatiale, avec une plus grande intensité au nord de la région et dans les zones de transition. L'étude fournit des preuves solides du réchauffement persistant dans les capitales amazoniens, contribuant ainsi à fournir des données cruciales pour les politiques d'adaptation climatique et la planification urbaine dans cette région sensible.

Mots-clés: Amazonie légale ; changement climatique ; réchauffement urbain.

1 INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC), in its Sixth Assessment Report (AR6), air temperatures are rising globally as a consequence of climate change, with particularly intensified effects in urban environments, where warming is potentiated by the formation of heat islands and rapid urbanization (IPCC, 2023; Shahfahad *et al.*, 2024). According to Liu *et al.* (2022), the warming of urban surfaces varies according to the size of the cities and their geographical location, generally being more pronounced in larger urban centers, where population density and the urbanization process contribute significantly to the rise in

temperatures. This phenomenon is aggravated in areas with compact infrastructure and scarcity of vegetation, which compromises natural cooling mechanisms (Cheng *et al.*, 2019; Hou; Estoque, 2020; Song; Park, 2021). In this scenario, it becomes crucial to understand how these dynamics manifest themselves in ecologically sensitive regions, such as the Amazon (Ferreira, Sávio José Filgueiras *et al.*, 2021; Furtado; Pereira; de Souza, 2024), where urban expansion can accentuate local and regional climatic effects.

The Amazon has experienced significant climate changes over the past five decades, most notably a persistent and significant increase in air temperature (Carvalho *et al.*, 2020; Da Silva *et al.*, 2019; Lucas *et al.*, 2021; Ritchie *et al.*, 2022). This continuous warming directly affects the region's main urban centers, amplifying challenges related to public health, infrastructure, and quality of life (Alves de Oliveira *et al.*, 2021; Ferreira, Mariana Abou Mourad *et al.*, 2023). Rising temperatures are one of the clearest expressions of climate change on a global and regional scale, with profound impacts on ecosystems, biodiversity, and the human populations that occupy this vast and sensitive portion of the national territory, directly affecting the well-being of urban communities (Tham *et al.*, 2020). Given this scenario, it becomes essential to investigate warming trends in Amazonian capitals in order to support public policies and guide urban planning, promoting effective adaptation and mitigation strategies in the face of adverse climate effects (Marengo *et al*., 2018).

Established scientific studies, such as those by Marengo *et al.* (2024) and Nobre *et al.* (2016), have repeatedly demonstrated the increase in surface temperatures across the vast Amazon region. This process is strongly associated with changes in land use and land cover, driven primarily by deforestation for agricultural, livestock, and infrastructure expansion. However, a review of the literature reveals that most research on Amazonian thermal dynamics has focused on rural areas or transition zones between forest and anthropized areas. While these approaches are essential for understanding the impacts of forest conversion, they ultimately leave significant gaps in understanding warming in urbanized areas. The capitals of the Amazonian states, which play central roles in regional administration, economy, and demography, concentrate a significant and growing portion of the population. This population density, coupled with disordered urban growth and the intensification of the heat island effect (Raiol *et al.*, 2024), makes these cities particularly vulnerable to the consequences of climate change.

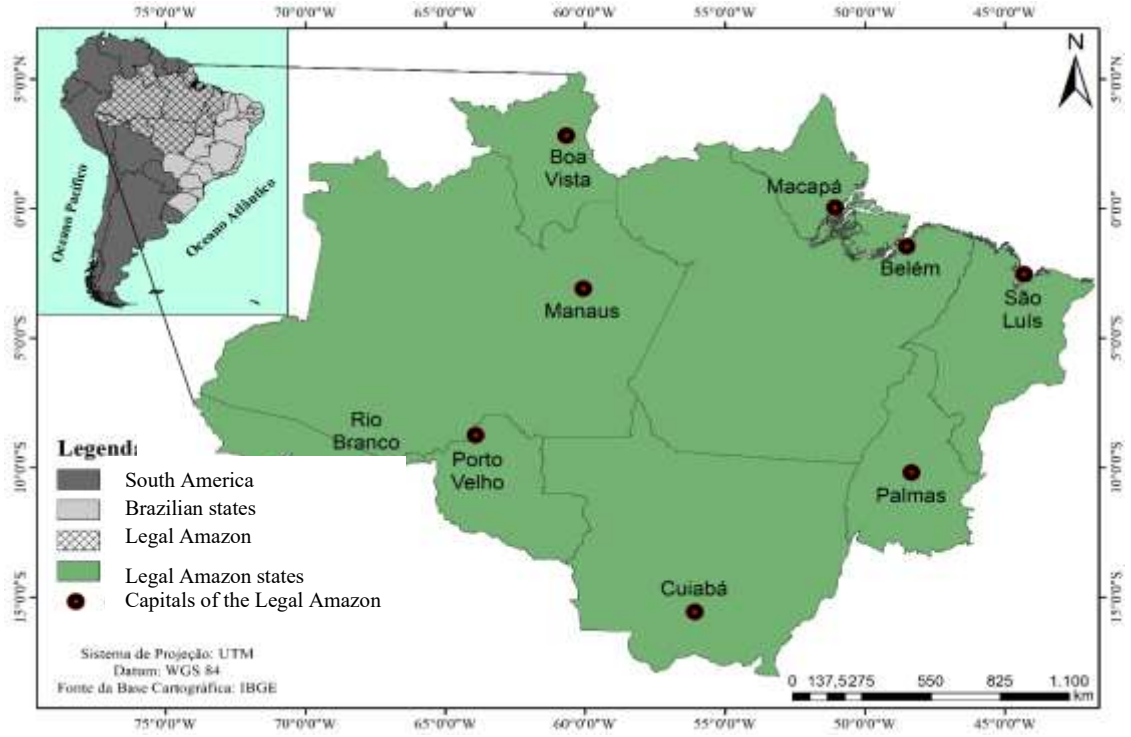
Although numerous studies have already documented rising temperatures in tropical regions, such as the Amazon (Almeida *et al.*, 2017; Da Silva *et al.*, 2019; de Souza *et al.*, 2025; Marengo *et al.*, 2024; Ritchie *et al.*, 2022), a significant gap persists in the continuous monitoring and in-depth analysis of warming in urban areas of the region, especially in the capital cities. These locations, increasingly impacted by changes in land use and the intensification of urban effects on the climate, require methodological approaches that consider their microclimatic specificities. In light of this context, the importance of advancing the investigation of changes and trends in air temperature in the capital cities of the Legal Amazon, which concentrate a growing portion of the regional population and present unique urban characteristics, becomes evident. The analysis of thermal evolution over half a century allows not only to quantify the magnitude of warming, but also to identify temporal and spatial patterns that contribute to the formulation of effective adaptive responses. Investigations with this focus are therefore fundamental to filling gaps in scientific literature and providing technical support for sustainable urban planning and the development of public policies aimed at mitigating the climate impacts on Amazonian urban centers. Thus, this study aims to analyze the temporal evolution of air temperature and its trend in the capitals of the Legal Amazon during the last half-century (1970-2024), with an emphasis on identifying warming trends.

2 MATERIALS AND METHODS

2.1 STUDY AREA

The study area encompasses the nine capitals of the Legal Amazon (Figure 1): Belém – PA, Boa Vista – RR, Cuiabá – MT, Macapá – AP, Manaus – AM, Palmas – TO, Porto Velho – RO, Rio Branco – AC, and São Luís – MA. These cities present distinct climatic, environmental, and urban characteristics, representing the socio-environmental diversity of the region. According to the last Brazilian Institute of Geography and Statistics (IBGE) census conducted in 2022 (IBGE, 2022), the total population of the 9 capitals (7,040,045) is equivalent to approximately 3.5% of the total population of Brazil (203,080,756 inhabitants).

Figure 1 – Geographic location of the state capitals of the Legal Amazon



Source: The authors (2025).

Based on the Köppen-Geiger 1936 climate classification (Köppen; Geiger, 1936; Lima *et al.*, 2023; Rahimi; Laux; Khalili, 2020), the Legal Amazon region has a climate type classified as "A" (corresponding to a tropical climate, characterized by average monthly temperatures always above 18°C throughout the year. This climate group is also characterized by high relative humidity and high rainfall, although the distribution of rainfall throughout the year may vary according to the subcategory). It is subdivided into three more specific types: type "*Af*" (humid tropical climate, without a dry season; all months with precipitation > 60 mm and average temperatures > 18°C); "*Am*" (monsoon tropical climate, with a short dry season; driest month with precipitation < 60 mm); and "*Aw*" (seasonal tropical climate, with a dry season in winter and rainfall concentrated in summer; driest month with precipitation < 60 mm). Throughout the year, air temperature does not show great variability, except in southern Amazonia. This occurs due to the influence of passing frontal systems (Marengo; Nobre; Culf, 1997).

In this region, there are two main meteorological systems that drive the high amount of rainfall between the months of December and April (Reboita *et al.*, 2010). In its northern portion, the ITCZ (Intertropical Convergence Zone) is active, reaching its southernmost position (~4°S)

between February and April. On the other hand, in the southern part of the Legal Amazon, in a NW-SE direction, from southwestern Amazonas to southeastern Mato Grosso, the SACZ (South Atlantic Convergence Zone) predominates, with its peak activity between December and February (Liebmann *et al.*, 1999).

2.2 CLIMATOLOGICAL AIR TEMPERATURE DATABASE

The air temperature variable at 2 meters used in this study was extracted from the ERA5 reanalysis, developed by the ECMWF (European Centre for Medium-Range Weather Forecasts) and made available by the C3S (Copernicus Climate Change Service) (Bell *et al.*, 2021; Hersbach *et al.*, 2020). ERA5 represents the fifth generation of global atmospheric reanalysis and provides consistent, high-quality estimates of various meteorological and climate variables, combining observations (from surface, balloons, satellites, and other sources) with sophisticated numerical models through a 4D-Var data assimilation system. (Gustafsson, 2007; Lorenc; Rawlins, 2005).

The air temperature at 2 meters (variable name: 2m_temperature, or t2m) refers to the estimate of the free air temperature at a height of 2 meters above the ground or vegetation surface. This estimate is derived from extrapolating the lowest pressure levels of the atmospheric model to the 2-meter level, considering local terrain and land cover conditions. Temperature values are provided in Kelvin (K) units, converted to degrees Celsius (°C) when necessary for easier interpretation and visualization. The spatial resolution of ERA5 is 0.25° × 0.25° latitude/longitude, which corresponds to approximately 31 km at the equator. The temporal resolution is hourly, with records available every 1 hour (UTC), allowing for detailed analyses of diurnal variations and extreme events. Data are available globally since 1950 (with more robust operational quality from 1979 onwards).

2.3 STATISTICAL PROCEDURES

2.3.1 The Mann-Kendall Test

The Mann-Kendall (MK) test (Kendall, 1955; Mann, 1945) is a widely used non-parametric test for detecting monotonic trends in time series. It assesses the significance of a trend without

requiring the data to be normally distributed. The test begins by calculating the S statistic using the following equation (Equation 1):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \quad (1)$$

where n is the total number of data points; x_j e x_i are the data values in the time series j and i ($j > i$), respectively, and $sgn(x_j - x_i)$ is the sign function, which can be calculated by the following equation (Equation 2):

$$sgn(x_j - x_i) = \begin{cases} +1, & se\ x_j - x_i > 0 \\ 0, & se\ x_j - x_i = 0 \\ -1, & se\ x_j - x_i < 0 \end{cases} \quad (2)$$

A positive value of *S* indicates an upward trend, and a negative value indicates a downward trend. The statistical distribution *S* is approximately normal when $n > 10$. The mean of *S* is zero, and the variance can be calculated as follows (Equation 3):

$$\mathrm{Var}(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)\right] \quad (3)$$

where *n* is the number of data points; *m* is the number of tied groups (a data set with the same value is considered a tied group); and t_i denotes the number of ties in extent *i*. In the case where the sample size, $n > 10$, the values of *S* and "Var" (*S*) are used to calculate the standard test Z_{MK} as follows (Equation 4):

$$Z_{MK} = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{Var}(S)}}, & se\ S > 0 \\ 0, & se\ S = 0 \\ \dfrac{S+1}{\sqrt{\mathrm{Var}(S)}}, & se\ S < 0 \end{cases} \quad (4)$$

The Z_{MK} score follows a normal distribution. Considering a significance level of α=0.05, corresponding to a 95% confidence interval for a two-tailed test, the critical values are -1.96 and +1.96. Thus, when the Z_{MK} value is negative and its absolute value exceeds 1.96, there is a statistically significant decreasing trend. On the other hand, if Z_{MK} is positive and greater than 1.96, the trend is increasing and significant. Z_{MK} values between -1.96 and +1.96 indicate no significant trend at the 5% level.

2.3.2 The Sen's slope estimator

The MK test, in conjunction with Sen's slope estimator (Sen, 1968), allows us to estimate the direction and magnitude of the trend, considering the conventional significance level of 0.05 (95%). This estimator calculates the median slope of all possible combinations between *N* pairs of points in the time series (Equation 5):

$$Q_i = \frac{X_j + X_k}{j - k}, i = 1, 2, 3, \ldots, N \quad (5)$$

where X_j and X_k are the data values at times *j* and *k (j > k)*, respectively. In Equation 5, $j > k$, the median of these *N* Q_i values is represented by the slope of the Sen estimate. The median of the Q_i values represents the magnitude of the trend. A positive value of the Sen slope indicates an increasing trend, while a negative value indicates a decreasing trend (Faquseh; Grossi, 2024).

2.3.3 The Pettitt Test

The Pettitt test (Pettitt, 1979) is a non-parametric test used to detect a significant change (or turning point) in a time series. It is particularly useful when you want to identify a point where the median of the series changes, without assuming a specific distribution for the data. In this study, the Pettitt test will be used to indicate in which year the turning point occurred, to separate the time series into two distinct periods, as used in several climatological studies (Ahmadi *et al.*, 2018; Mallakpour; Villarini, 2016; Rybski; Neumann, 2011; Serinaldi; Kilsby, 2016; Verma; Prasad; Verma, 2022; Zarenistanak; Dhorde; KripalaniI, 2014). This test is presented in such a way that *k* is the candidate index for a turning point (or break point) and the values x_1, x_2, ..., x_n

are values from the time series, arranged in ascending order (Equation 6). The absolute value is used because we are interested in the intensity of the change, regardless of the direction:

$$k = \left| \max_{k} \sum_{i=1}^{k} \sum_{j=i+1}^{n} sgn(x_j - x_i) \right|, 1 < k < n \quad (6)$$

where $sgn(x_j - x_i)$ is the sign function (Equation 7).

$$sgn(x_j - x_i) = \begin{cases} +1, & se\ x_j - x_i > 0 \\ 0, & se\ x_j - x_i = 0 \\ -1, & se\ x_j - x_i < 0 \end{cases} \quad (7)$$

The point of change in the series is located in the Pettitt test when *k* reaches its maximum value, provided the statistic is significant. The probability of significance of *k* is approximated to $p \leq 0.05$ with (Equation 8)

$$p \approx 2exp\left(\frac{-6k^2}{n^3 + n^2}\right) \quad (8)$$

As long as the *p*-value is greater than the specified significance level α (0.05), the null hypothesis (H_0 indicates homogeneous data) can be accepted and there is no change point in the data series. Conversely, for *p*-values less than α (0.05), the null hypothesis is rejected and the alternative hypothesis (H_1 indicates a change has occurred) is considered.

2.4 WARMING STRIPES

To illustrate the annual temperature anomalies relative to the 1971-2000 average of the ERA5 data, the methodology developed by Ed Hawkins (Hawkins *et al.*, 2025) was chosen. This is a simple and impactful way to visualize warming in the capitals of the Legal Amazon; its strength lies in the visual clarity of the trend. In Hawkins' visualizations, the use of warm and cool colors clearly and accessibly communicates climate change. Warm colors (shades of red)

indicate warming, while cool colors (shades of blue) suggest cooling; the darker the color, the greater the magnitude of the anomaly, facilitating comprehension by diverse audiences (O'Connor, 2023).

2.5 DATA PROCESSING

To acquire the ERA5 annual average temperature data, a script was developed in the Python language (Mehare; Anilkumar; Usmani, 2023). In simple terms, the code automates the download, processing, and export of annual air temperature data at 2 meters for a specific point (defined by latitude and longitude), using ERA5 reanalysis. It accesses the Copernicus Climate Data Store API to obtain monthly temperature averages since 1970, calculates anomalies based on the climatology of the period 1971–2000, and exports the results in CSV files, both in annual resolution.

Using the Python programming language, statistics were calculated for the Mann-Kendall test, Sen's slope, and the Pettitt test. In summary, the steps adopted in the code performed a trend analysis and change detection in annual time series of average temperature, based on data in CSV format. It uses the Pettitt test to identify points of abrupt change, the Mann-Kendall test to verify the presence of a monotonic trend, and Sen's slope to estimate the rate of temperature variation over time.

The Warming Stripes were developed with code to graphically represent the annual air temperature anomalies of the capitals of the states in the Legal Amazon, between 1970 and 2024, based on ERA5 data. This code used a color gradient from blue (negative anomalies) to red (positive), assigning a color to each year according to the magnitude of the anomaly, composing a final high-resolution figure for climate communication and dissemination.

Finally, annual temperature trend graphs were created in Microsoft Excel, based on the results obtained from the Pettitt and Mann-Kendall statistical tests. In Excel, line graphs representing the temperature time series were created, with the addition of visual elements such as the year of change detected, allowing for a clear and accessible interpretation of climate patterns over time. This approach combined the robustness of statistical analyses with the graphical flexibility of Excel for presentation and scientific communication purposes.

4 RESULTS AND DISCUSSION

4.1 STATISTICAL ANALYSIS

Table 1 presents the results of the Z_{MK} statistic, the decline of Sen, and the p-value associated with the adopted statistics for the annual time series of air temperature at 2 meters in the analyzed capitals. The results of the Z_{MK} test revealed significant increasing trends ($p < 0.0001$) in all capitals of the Legal Amazon, confirming regional warming throughout the evaluated period, evidencing the presence of consistent and non-random warming in the time series. These results are consistent with recent research that points to an increase in air temperature in the Amazon (Almeida *et al.*, 2017; Da Silva *et al.*, 2019; Dias *et al.*, 2021; Victoria *et al.*, 1998).

Z_{MK} values ranged from 5.78 (Cuiabá) to 7.23 (Macapá), with the highest values observed in the cities of Macapá (Z_{MK} = 7.23) and Belém (Z_{MK} = 7.06), indicating more pronounced and consistent warming trends. The Sen slope, which estimates the annual rate of change, ranged from 0.019°C/year (São Luís) to 0.032°C/year (Boa Vista), reflecting a significant increase in average temperatures over the years. The high statistical significance, combined with moderate to high slopes, reinforces the robustness of the trends detected. Although São Luís presented the lowest Sen slope, the Z_{MK} value (6.43) suggests that this trend, although less intense, is highly consistent over time.

The analysis of warming trends in the capitals of Northern Brazil, evidenced by high Z_{MK} values and positive Sen slope rates, corroborates broader studies on climate change in the Amazon region. Research encompassing multiple locations and longer time series, using robust statistical methodologies such as the Mann-Kendall test, has also identified a predominant pattern of increasing average temperatures, particularly pronounced since the 1990s (Penereiro *et al.*, 2018). This convergence of results, both at the level of specific capitals and on a regional scale, underscores the consistency of the observed warming phenomenon, reinforcing the perception that the Amazon is an area particularly sensitive to global and regional climate change.

Table 1 – Results of the Mann–Kendall test (Z_{MK}), Sen decline and associated p-value, for annual temperature time series from 1970-2024

City	Z_{MK}	Sen decline (°C/year)	p-value
Belém	7.06	0.027	<0.0001
Boa Vista	6.43	0.032	<0.0001
Cuiabá	5.78	0.023	<0.0001
Macapá	7.23	0.027	<0.0001
Manaus	6.11	0.023	<0.0001
Palmas	5.92	0.025	<0.0001
Porto Velho	6.87	0.024	<0.0001
Rio Branco	5.98	0.021	<0.0001
São Luís	6.43	0.019	<0.0001

Source: The authors (2025).

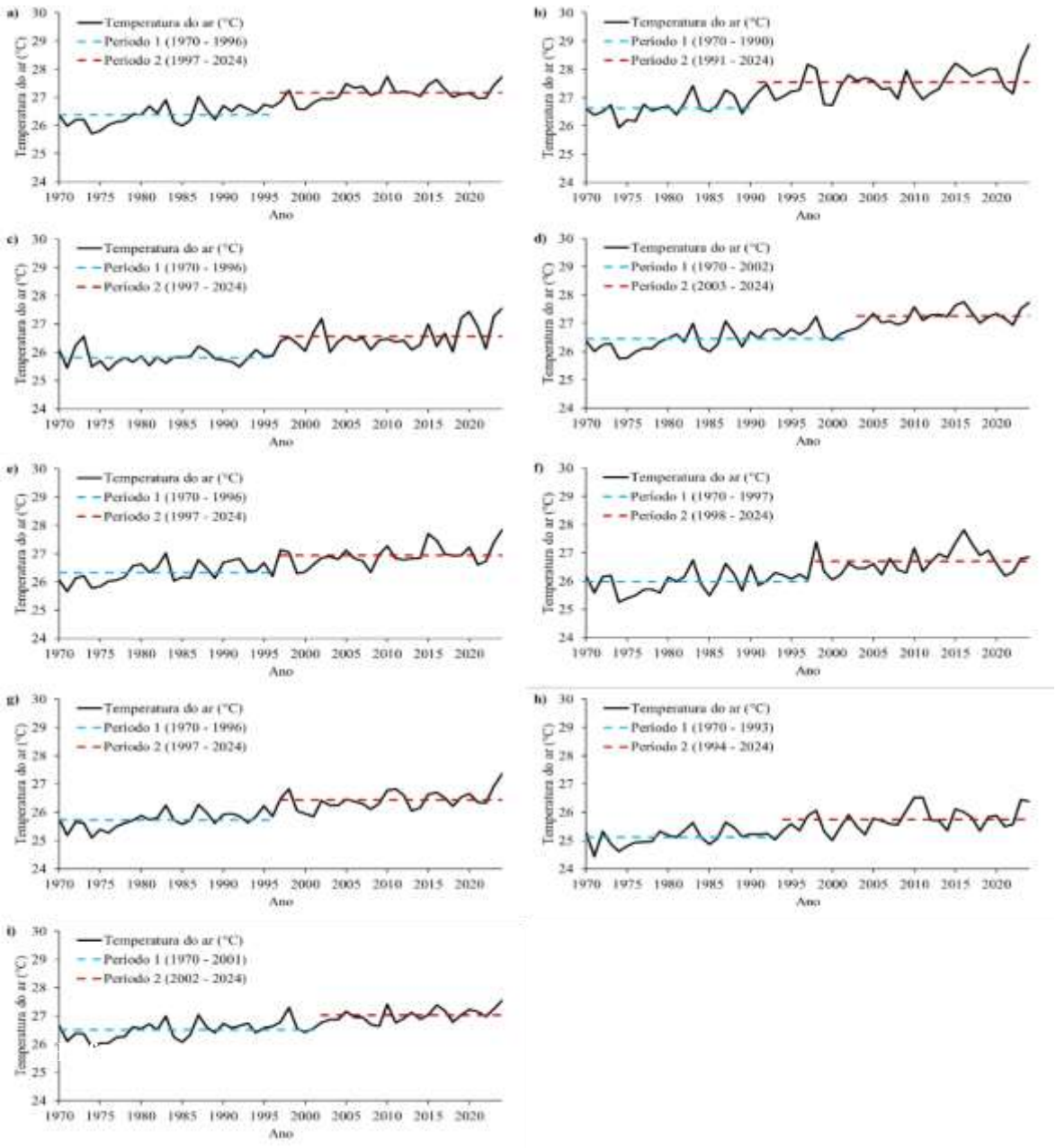
The detection of statistically significant warming trends, such as those presented in Table 1, aligns with IPCC projections and observations, which point to a warming of the global climate system (IPCC, 2023). Although natural variability, including phenomena such as El Niño, can influence interannual and seasonal trends (Jiménez-Muñoz *et al.*, 2016; Li *et al.*, 2011; Moura *et al.*, 2019), the consistency of long-term trends suggests a strong component associated with anthropogenic climate change and land-use changes in the region (Almeida *et al.*, 2017). Understanding these trends and their potential drivers is crucial for the development and implementation of effective public policies and adaptation strategies that consider the specific vulnerabilities of each locality, given a scenario of evident warming trends (Green; Armstrong; Soon, 2009).

It is worth highlighting that the Z_{MK} values and Sen's slope did not show direct proportionality, corroborating the complementary nature of these metrics. While the Mann-Kendall test detects the existence and statistical significance of the trend, Sen's slope quantifies its magnitude (Aditya; Gusmayanti; Sudrajat, 2021). Furthermore, as observed by Yue, Pilon, and Cavadias (2002), although the Mann-Kendall test is effective in indicating the existence of monotonic trends in time series, it does not provide information on the rate of change, a role played by Sen's slope. This combined approach is especially useful in climate studies, where the trend can be statistically significant even with subtle variations (i.e., with a low slope), as verified in the case of São Luís. Thus, locations with greater statistical consistency are not always those

with a higher rate of warming, which emphasizes the need for joint interpretation of these statistics.

Figure 2 illustrates the time series (1970–2024) of air temperature and the division of this series into two distinct periods, after applying the Pettitt test, for the capitals of the Legal Amazon. The Pettitt test allowed the identification of change points in the time series, suggesting a significant change in temperature behavior from the 1990s onwards. Most cities showed a change point in 1997 (Belém, Cuiabá, Manaus, Porto Velho), with exceptions such as Boa Vista (1991), Rio Branco (1994), Palmas (1998), São Luís (2002) and Macapá (2003). These results indicate an intensification of warming from the mid-1990s onwards in much of the region.

Figure 2 – Graphical representation of the annual temperature series (1970-2024) for Belém (a), Boa Vista (b), Cuiabá (c), Macapá (d), Manaus (e), Palmas (f), Porto Velho (g), Rio Branco (h) and São Luís (i). The dashed lines indicate the results found by the Pettitt test, where the blue colors indicate Period 1 (before the change) and the red colors indicate Period 2 (after the change)



Source: The authors (2025).

The identification of change points in temperature time series, predominantly in the 1990s and early 2000s, as detected by the Pettitt test, provides further evidence on the dynamics of warming in the Legal Amazon. The concentration of change points in this specific period suggests an inflection point or acceleration in the regional warming process, aligning

with observations from other studies that also point to the 1990s as a key period for the intensification of positive temperature trends in the Legal Amazon. A study by Bodas Terassi et al. (2024) reveals that, during the 1990s and 2000s, there was an abrupt change, or pattern break, in climate data related to extreme temperatures. This change was not gradual, but rather a discontinuity, indicating that something significant may have influenced the climate during this period; the accelerated urbanization process (more buildings, more asphalt, less vegetation) may have altered the local microclimate, contributing to increased temperatures or a higher frequency of thermal extremes.

The change in the temperature regime from the identified tipping points may be associated with a combination of factors, including the intensification of the greenhouse effect on a global scale, natural climate variability, and regional changes in land use and land cover, such as deforestation (Bodas Terassi et al., 2024). Studies indicate that the climate changes observed in the Legal Amazon, including the increase in temperatures, are consistent with global warming (IPCC, 2023; Harris; Huntingford; Cox, 2008). Tipping point analysis, as performed with the Pettitt test, is fundamental to understanding not only the magnitude of the warming trend but also its temporal evolution, identifying periods of more accelerated changes that can significantly impact ecosystems and local populations, requiring adjustments in response and coping strategies.

Complementing Figure 2, Table 2 presents the long-term averages of annual temperatures (1970–2024) for the capitals of the Legal Amazon, segmented into two distinct periods, identified by the Pettitt test. The results reinforce the trend of increasing average annual temperatures in the capitals of the Legal Amazon, showing a consistent increase in average annual temperatures in all capitals between the two distinct periods. The observed variations (range between periods) ranged from 0.52°C in São Luís to 0.91°C in Boa Vista, indicating significant warming over the last few decades.

The largest temperature variations were observed in Boa Vista (0.91°C), Macapá (0.81°C), and Belém (0.80°C), all located in the northern part of the region, suggesting a possible intensification of the effects of global warming in this sub-region. In contrast, São Luís (0.52°C) and Rio Branco (0.63°C) showed the smallest variations, although still significant from a climatic point of view. The capital of Mato Grosso, Cuiabá, stood out for showing an increase of 0.75°C. This amplitude, for example, aligns with the observation that Amazon-Cerrado transition areas

may experience more pronounced climate changes due to the combination of climatic and anthropogenic influences, corroborating studies that point to a more pronounced warming in transition areas between the Cerrado and the Amazon rainforest (Bodas Terassi *et al.*, 2024; Joseph; Souza; Sabino, 2021; Marengo *et al.*, 2022).

Table 2 – Long-term averages (1970-2024) of annual temperature series for the capitals of the Legal Amazon region during the different periods identified by the Pettitt test

City	Period 1	Period 2	Variation
Belém	26.4°C	27.2°C	0.80°C
Boa Vista	26.4°C	27.5°C	0.91°C
Cuiabá	25.8°C	26.6°C	0.75°C
Macapá	26.4°C	27.3°C	0.81°C
Manaus	26.3°C	26.9°C	0.62°C
Palmas	26.0°C	26.7°C	0.73°C
Porto Velho	25.7°C	26.4°C	0.71°C
Rio Branco	25.1°C	25.7°C	0.63°C
São Luís	26.5°C	27.0°C	0.52°C

Source: The authors (2025).

The comparative analysis of average temperatures between Periods 1 and 2 (Table 2) quantifies the magnitude of post-tipping point warming in each capital city. The observed range, varying from 0.52°C to 0.91°C, represents a substantial increase in the average annual temperature over a period of a few decades, reinforcing the robustness of the warming signal in the region. The spatial heterogeneity of the warming ranges, with higher values in the North (Boa Vista, Macapá, Belém) and in transition areas such as Cuiabá, suggests the influence of regional factors modulating the response to global warming.

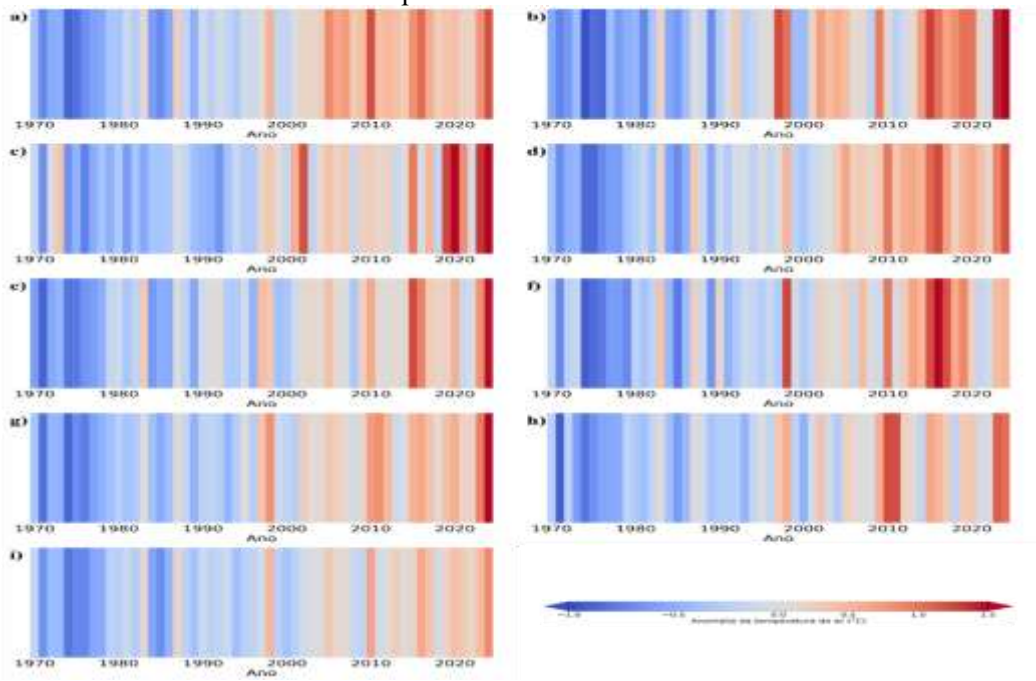
4.3 WARMING STRIPES

Based on the warming stripes generated from annual air temperature anomalies (1970–2024) for the capitals of the Legal Amazon (Figure 3), a clear and consistent warming trend is observed over the last five decades. The graphs reveal a striking visual transition from bluish tones (negative anomalies) to reddish tones (positive anomalies), indicating a gradual and

continuous increase in average annual temperatures in all the capitals analyzed. A predominance of bluish tones is observed until the mid-1980s, followed by a progressive increase in the frequency and intensity of reddish tones, indicating persistent positive anomalies from the 1990s onwards. This pattern intensifies in the 2000s and 2010s, reflecting an accelerated regional warming process.

Among the capital cities analyzed, Boa Vista presents one of the most striking warming trends, with anomalies exceeding +1.5°C in 2024, a value that represents the peak of the time series for this location. Other capital cities, such as Cuiabá, Macapá, and Belém, also recorded anomalies exceeding +1.0°C in several recent years. Capital cities located in the western and northeastern portions of the Legal Amazon, such as Rio Branco, Porto Velho, and São Luís, also demonstrated a gradual increase in positive anomalies, especially after the year 2000. The year 2024 stands out as one of the hottest in the entire time series for most capital cities, with a positive anomaly of around +1.4°C, which may be associated with the intensification of large-scale climatic phenomena, such as the El Niño phenomenon (Espinoza *et al.*, 2024; Santos de Lima *et al.*, 2024), in addition to the global warming trend.

Figure 3 – Warming stripes of air temperature anomalies from annual series (1970-2024) for Belém (a), Boa Vista (b), Cuiabá (c), Macapá (d), Manaus (e), Palmas (f), Porto Velho (g), Rio Branco (h) and São Luís (i). Colors in shades of blue indicate negative anomalies, while colors in shades of red indicate positive anomalies



Source: The authors (2025).

4 CONCLUSIONS

In summary, the results point to a regional scenario of significant and progressive warming in the Amazonian capitals, with important variations in both the intensity and statistical consistency of the trends. The results obtained through the application of the Mann-Kendall test, Sen estimator, and Pettitt test unequivocally evidenced a consistent and statistically significant warming process in all the capitals analyzed. The identification of change points by the Pettitt test allowed the series to be segmented into two distinct periods, revealing that most capitals experienced a significant change in thermal behavior from the 1990s onwards, especially in 1997, the year in which four capitals (Belém, Cuiabá, Manaus, and Porto Velho) presented breakpoints.

These results contribute to filling gaps in the scientific literature on thermal dynamics in Amazonian urban centers, offering a detailed characterization of the temporal evolution and magnitude of warming in the region's capitals. The contributions of the results can range from public health and urban thermal comfort issues to aspects related to energy demand and infrastructure planning. These findings reinforce the importance of regionalized climate adaptation strategies, considering the particularities of each capital city analyzed. These data highlight the importance of continuous monitoring of climatic variables and the implementation of public policies for adaptation and mitigation in the face of observed warming. This represents a growing challenge for public managers and urban planners, demanding specific adaptive mitigation strategies that consider the climatic and socio-environmental particularities of each location.

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Increasing drought and declining precipitation in the Amazon:
a statistical assessment of climate extremes over nearly half a century

Secas em ascensão e precipitação em declínio na Amazônia:
diagnóstico estatístico de extremos climáticos ao longo de quase meio século

Aumento de las sequías y disminución de la precipitación en la Amazonía:
diagnóstico estadístico de los extremos climáticos a lo largo de casi medio siglo

Sécheresses en hausse et précipitations en baisse en Amazonie :
analyse statistique des extrêmes climatiques sur près d'un demi-siècle

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Abstract
The objective of this study is to identify changes in precipitation patterns and the occurrence of extreme events in the Amazon from 1979 to 2024. The analysis was regionalized into five sub-regions: Northwest (NW), Northeast (NE), West (W), East (E), and Southeast (SE). Monthly precipitation data from the National Oceanic and Atmospheric Administration (NOAA), via the Climate Prediction Center (CPC), were used. Extreme dry and wet events were defined based on values below the 15% percentile and above the 85% percentile, respectively. To identify temporal trends, simple linear regression was applied, and statistical significance was assessed using the Student's t-test. Results show a statistically significant reduction in monthly precipitation, particularly in the E and SE sub-regions. There was also an increase in the frequency of extreme dry events across all sub-regions, with SE showing the highest intensity, suggesting growing vulnerability to drought. In contrast, extreme wet events showed a

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decreasing trend, although with less statistical consistency. The findings indicate that the Amazon rainfall regime has become more irregular, with a predominance of dry extremes, posing risks to ecological sustainability, water security, and local population resilience. These results underscore the urgent need for climate adaptation policies and regional climate monitoring systems in the Amazon.

Keywords: climate change; linear regression; ENSO.

Resumo

Este estudo tem como objetivo identificar mudanças nos padrões de precipitação e na ocorrência de eventos extremos na Amazônia, no período de 1979 a 2024. As análises foram regionalizadas em cinco sub-regiões: Noroeste (NW), Nordeste (NE), Oeste (W), Leste (E) e Sudeste (SE). Utilizou-se de dados mensais de precipitação do *National Oceanic and Atmospheric Administration* (NOAA), via *Climate Prediction Center* (CPC). Eventos extremos secos e chuvosos foram definidos com base nos valores abaixo do percentil 15% e acima do percentil 85%, respectivamente. Para identificar tendências temporais, aplicou-se regressão linear simples, com teste t de *Student* para verificar a significância estatística. Os resultados apontam redução significativa na precipitação mensal, especialmente nas sub-regiões E e SE. Verificou-se também aumento na frequência de eventos secos extremos em todas as sub-regiões, com maior intensidade em SE, sugerindo crescente vulnerabilidade à estiagem. Os eventos extremos chuvosos apresentaram tendência de redução, mas com menor consistência estatística. Conclui-se que o regime pluviométrico da Amazônia se tornou mais irregular, com predomínio de extremos secos, o que acarreta riscos à sustentabilidade ecológica, à segurança hídrica e à resiliência das populações. Os resultados reforçam a necessidade de políticas públicas de adaptação climática e de sistemas regionais de monitoramento.

Palavras-chave: mudanças climáticas; regressão linear; ENOS.

Resumen

Este estudio tiene como objetivo identificar cambios en los patrones de precipitación y en la ocurrencia de eventos extremos en la Amazonía entre 1979 y 2024. Los análisis se regionalizaron en cinco subregiones: Noroeste (NW), Noreste (NE), Oeste (W), Este (E) y Sureste (SE). Se utilizaron datos mensuales de precipitación del National Oceanic and Atmospheric Administration (NOAA), a través del Climate Prediction Center (CPC). Los eventos extremos secos y lluviosos se definieron con base en valores por debajo del percentil 15% y por encima del percentil 85%, respectivamente. Para identificar tendencias temporales, se aplicó regresión lineal simple, con la prueba t de *Student* para verificar la significancia estadística. Los resultados señalan una reducción significativa en la precipitación mensual, especialmente en las subregiones E y SE. También se observó un aumento en la frecuencia de eventos secos extremos en todas las subregiones, con mayor intensidad en SE, lo que sugiere una creciente vulnerabilidad a la sequía. Los eventos extremos lluviosos mostraron una

tendencia a la disminución, aunque con menor consistencia estadística. Se concluye que el régimen pluviométrico de la Amazonía se ha vuelto más irregular, con predominio de extremos secos, lo que genera riesgos para la sostenibilidad ecológica, la seguridad hídrica y la resiliencia de las poblaciones. Los resultados refuerzan la necesidad de políticas públicas de adaptación climática y de sistemas regionales de monitoreo.

Palabras clave: cambio climático; regresión lineal; ENSO.

Résumé
Cette étude vise à identifier les changements dans les régimes de précipitations et l'occurrence d'événements extrêmes en Amazonie sur la période allant de 1979 à 2024. Les analyses ont été régionalisées en cinq sous-régions : Nord-Ouest (NW), Nord-Est (NE), Ouest (W), Est (E) et Sud-Est (SE). Les données mensuelles de précipitations proviennent de la National Oceanic and Atmospheric Administration (NOAA), via le Climate Prediction Center (CPC). Les événements extrêmes secs et humides ont été définis sur la base de valeurs inférieures au 15% et supérieures au 85%, respectivement. Pour identifier les tendances temporelles, une régression linéaire simple a été appliquée, accompagnée du test t de *Student* pour en vérifier la signification statistique. Les résultats indiquent une diminution significative des précipitations mensuelles, en particulier dans les sous-régions E et SE. Une augmentation de la fréquence des épisodes extrêmes de sécheresse a été observée dans toutes les sous-régions, avec une intensité plus marquée dans la région SE, suggérant une vulnérabilité croissante à l'aridité. Les épisodes extrêmes de précipitations montrent une tendance à la baisse, bien que de manière statistiquement moins consistante. Il en ressort que le régime pluviométrique amazonien est devenu plus irrégulier, avec une prédominance des extrêmes secs, ce qui représente un risque pour la durabilité écologique, la sécurité hydrique et la résilience des populations. Ces résultats soulignent la nécessité de politiques d'adaptation climatique et de systèmes régionaux de surveillance.

Mots-clés : changement climatique ; régression linéaire ; ENSO.

1 INTRODUCTION

The Amazon region is home to the largest tropical rainforest on the planet and one of the world's largest hydrographic networks. Furthermore, studies conducted by Nobre *et al.* (2016) highlight the crucial role this region plays in climate regulation, both regionally and globally. Precipitation is one of the region's main meteorological elements, sustaining diverse ecosystems, the hydrological cycle, and the socioeconomic activities of local populations, including agriculture, fishing, river transport, and water supply (Marengo, 2008). The region is

characterized by a predominantly high precipitation regime, with annual averages between 1,500 and 3,000 mm across much of its area, marked by moderate seasonality and a strong influence from large-scale atmospheric systems (Figueroa; Nobre, 1990).

Rainfall distribution in the Amazon is modulated by climate variability phenomena related to Sea Surface Temperature (SST) anomalies in the tropical Pacific and Atlantic oceans. The *El Niño*-Southern Oscillation (ENSO) phenomenon, with its *El Niño* (anomalous warming of SSTs) and *La Niña* (anomalous cooling of SSTs) phases in the Equatorial Pacific, is associated with rainfall deficits and excesses in the region, especially during the austral summer (Aceituno, 1988; Nobre; Shukla, 1996; Marengo *et al.*, 2001; Ronchail *et al.*, 2002). In addition to ENSO, the Atlantic Dipole pattern, characterized by opposing thermal anomalies between the northern and southern basins of the tropical Atlantic, also influences the regional rainfall regime (Souza *et al.*, 2000).

These climate variability phenomena modulate the action and intensity of meteorological systems that cause precipitation in the Amazon, such as the Inter-Tropical Convergence Zone (ITCZ), the Bolivian High, Upper-Level Cyclonic Vortices (ULCVs), the South Atlantic Convergence Zone (SACZ), frontal systems, the South Atlantic Subtropical High (SASH), and mesoscale convective systems (Rao; Hada, 1990, Kodama, 1992, Gan; Kousky, 1986; Kousky; Kagano, 1981; Ferreira *et al.,* 2009; Oliveira, 1986; Satyamurty *et al.,* 2013; Cohen *et al.,* 1995).

Since 2000, there has been growing concern about climate change and its potential adverse consequences. Reports from the Intergovernmental Panel on Climate Change (IPCC) indicate changes in rainfall patterns in various parts of the world, with an increase in the frequency and intensity of extreme events in the Amazon (IPCC, 2021), and several studies have identified signs of these changes in the region. Brito *et al.* (2014) analyzed different types of extreme precipitation events in the region between 1998 and 2013, evaluating their frequency, intensity, and contribution to the climatology of accumulated precipitation, observing an intensification of these events in the last seven years of the period, peaking between 2011 and 2012. Santos *et al.* (2015), in turn, investigated trends in daily precipitation for the Brazilian Amazon and identified a significant increase in the number of days with extreme precipitation in the northwestern portion of the region, while in the south a trend of reduction in these events was observed. These changes, often associated with climate variability phenomena such as *El Niño/La Niña*, result in profound socio-environmental impacts, including increased wildfires, rises or falls in river levels, and damage to transportation and biodiversity (Marengo *et al.*, 2024).

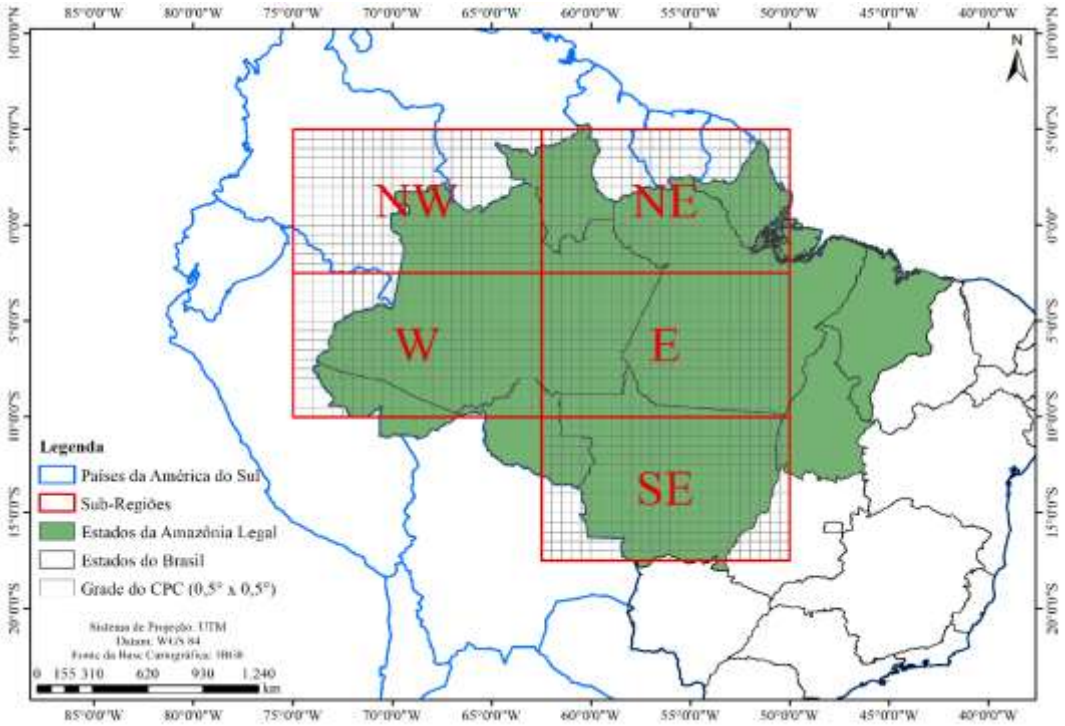
Despite increasing scientific and political attention, gaps persist in understanding the spatial and temporal variability of precipitation and its extremes in the Amazon. In this context, this study aimed to identify changes in precipitation patterns and the occurrence of extreme events in a regionalized manner in the Amazon, throughout the period from 1979 to 2024. Using simple linear regression techniques, it seeks to detect temporal trends and assess their statistical significance, contributing to a more accurate regional climate diagnosis and supporting adaptation strategies and climate risk management in the region.

2 MATERIALS AND METHODS

2.1 STUDY AREA

The study area was divided based on the geographic location of the sectors of the Amazon region, using five sub-regions delimited by latitudinal and longitudinal bands. The methodology follows a criterion similar to that adopted by Alves *et al.* (2013), who employed this approach to classify drought years in the Amazon. The defined sub-regions were: Northwest (NW): 75°W to 62.5°W and 5°N to 2.5°S; Northeast (NE): 62.5°W to 50°W and 5°N to 2.5°S; West (W): 75°W to 62.5°W and 2.5°S to 10°S; East (E): 62.5°W to 50°W and 2.5°S to 10°S; and Southeast (SE): 62.5°W to 50°W and 10°S to 17.5°S (Figure 1). The Northeast sub-region includes the capitals Boa Vista-RR and Macapá-AP; the West sub-region includes the capitals Rio Branco-AC and Porto Velho-RO; and the Southeast sub-region includes the capital Cuiabá-MG. These subdivisions represent areas with distinct climatic characteristics within the Amazon, allowing for a regionalized analysis of precipitation variability and the occurrence of extreme events.

Figure 1 – Study area, highlighting the five sub-regions of the Amazon used in the analysis: Northwest (NW), Northeast (NE), West (W), East (E), and Southeast (SE)



Source: The authors (2025).

2.2 DATA

Monthly accumulated precipitation data from the National Oceanic and Atmospheric Administration (NOAA), provided by the Climate Prediction Center (CPC), were used. This data consists of a dense observational network distributed around the world, interpolated on a grid of 0.5° latitude by 0.5° longitude (Silva *et al.*, 2007), as shown in Figure 1. This dataset was generated based on observations collected by orbital satellite platforms, interpolated with data from surface stations, and adjusted with estimates from the satellites themselves. This type of data was chosen considering the scarcity of conventional measurements with long historical series in the Amazon, making it suitable for climatological studies (at least 30 years). The period analyzed was from January 1979 to December 2024. Monthly spatial averages were calculated for each of the five delimited areas, resulting in time series representative of each region.

For the calculation of climatology and as a basis for identifying extreme events, the period from 1981 to 2010 was adopted, as recommended by the World Meteorological Organization (WMO, 2017).

2.3 METHODOLOGY

To identify the annual and monthly climatology of the sub-regions, the annual and monthly arithmetic mean (Equation 1) of precipitation for the period from 1981 to 2010 was calculated.

$$\overline{Prp} = \frac{1}{n}\sum_{i=1}^{n} Prp_i \qquad \text{(Equation 1)}$$

Where: $\overline{Prp}$ is the average annual or monthly climatological precipitation; *Prp* is the precipitation value in year or month i of the reference period; n is the number of years in the reference period (n = 30, in the case of 1981 to 2010).

The identification of extreme precipitation events was carried out based on the statistical methodology proposed by Xavier (2002), similar to that applied in Tavares *et al.* (2021), which uses the empirical distribution of data to calculate percentiles. This approach is recommended when one wishes to avoid assumptions about the shape of the distribution (e.g., normality), being particularly useful for rainfall data that frequently exhibit asymmetries. Thus, given a set of n monthly precipitation values $x1$, $x2$, …, xn, ordered in ascending order, the percentile value p (where $0<p<1$) is obtained by linear interpolation between the ordered elements, according to Equation 2:

$$P_p = x_i + (n.p - i).(x_{i+1} - x_i) \qquad \text{(Equation 2)}$$

Where: P_p is the value of the percentile p; x_i is the value of the i-th element of the ordered series and $i=\lfloor n \cdot p \rfloor$, with $\lfloor \cdot \rfloor$ being the integer part.

The following thresholds were used to define extreme events: dry extreme: monthly precipitation below the 15th percentile ($P0.15$) and wet extreme: monthly precipitation above the 85th percentile ($P0.85$).

The percentile calculation was performed individually for each month of the year and for each sub-region, in order to consider the seasonality of precipitation. Thus, all Januarys were grouped together, as were all Februarys, and so on, forming 12 monthly distributions per sub-region for the climatological reference period (1981 to 2010). This approach allowed the identification, for each month and region, of significant deviations from the normal precipitation behavior, distinguishing it from parametric methods such as the Standardized

Precipitation Index (SPI), which require assumptions about the statistical distribution of the data (McKee *et al.*, 1993).

To analyze temporal trends in the precipitation series and the annual frequency of extreme events (dry and wet), simple linear regression was applied, a statistical method widely used to describe the relationship between a dependent variable and an independent variable (Montgomery; Runger, 2003). Simple linear regression models a variable y (in this study, monthly precipitation or the number of months in the year with extreme events) as a function of time x (represented by the year or the month number throughout the time series). The equation of the fitted line is given by Equation 3.

$$y = a + bx \qquad \text{(Equation 3)}$$

Where: y is the dependent variable (precipitation or number of events per year), x is the independent variable (time), a is the intercept, which represents the expected value of y when x=0, b is the slope (or inclination of the line), which represents the rate of change of y over time.

A positive value of b indicates an increasing trend, while a negative value indicates a decreasing trend. The slope coefficient (b) was estimated using the least squares method, which minimizes the sum of the squares of the residuals between the observed values and the fitted values of the line.

The regression was applied in two ways: to the monthly precipitation time series (1979 to 2024) in each sub-region, to identify seasonal and interannual trends; and to the annual series of the number of months with extreme dry and rainy events, to verify changes in the frequency of these events over time.

In this way, it was possible to objectively assess the presence of trends of intensification or reduction of precipitation and the frequency of extreme events in different sectors of the Amazon. Such trends may be associated with changes in the regional and global climate, possibly linked to climate change processes (IPCC, 2021).

To assess the statistical significance of the trends identified in the time series (1979 to 2024) of monthly precipitation and the number of months in the year with extreme events (dry and rainy), the Student's t-test (t) was applied to the slope of the line obtained by simple linear regression (Equation 4). This test verifies the null hypothesis that the slope b is equal to zero, that is, that there is no significant trend over time (Montgomery; Runger, 2003; Wilks, 2011).

The significance of the test is assessed by the p-value corresponding to the value of t, considering the degrees of freedom $n-2$, where n is the total number of observations. Values

of p less than 0.05 indicate that the trend is statistically significant at the 5% level, rejecting the null hypothesis.

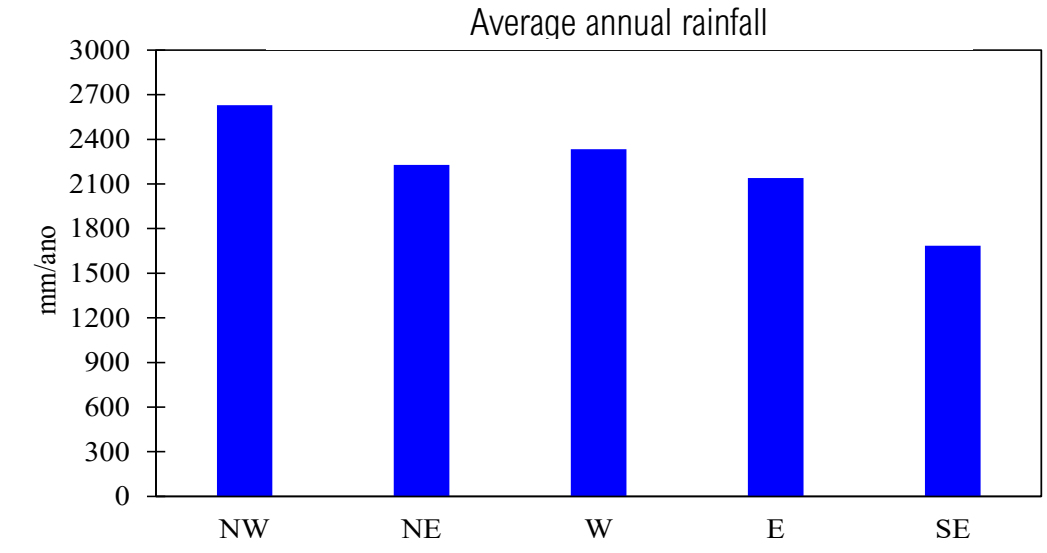
$$t = \frac{b}{SE(b)} \qquad \text{(Equation 4)}$$

Where: b is the slope of the regression line; $SE(b)$ is the standard error associated with the slope.

3 RESULTS AND DISCUSSIONS

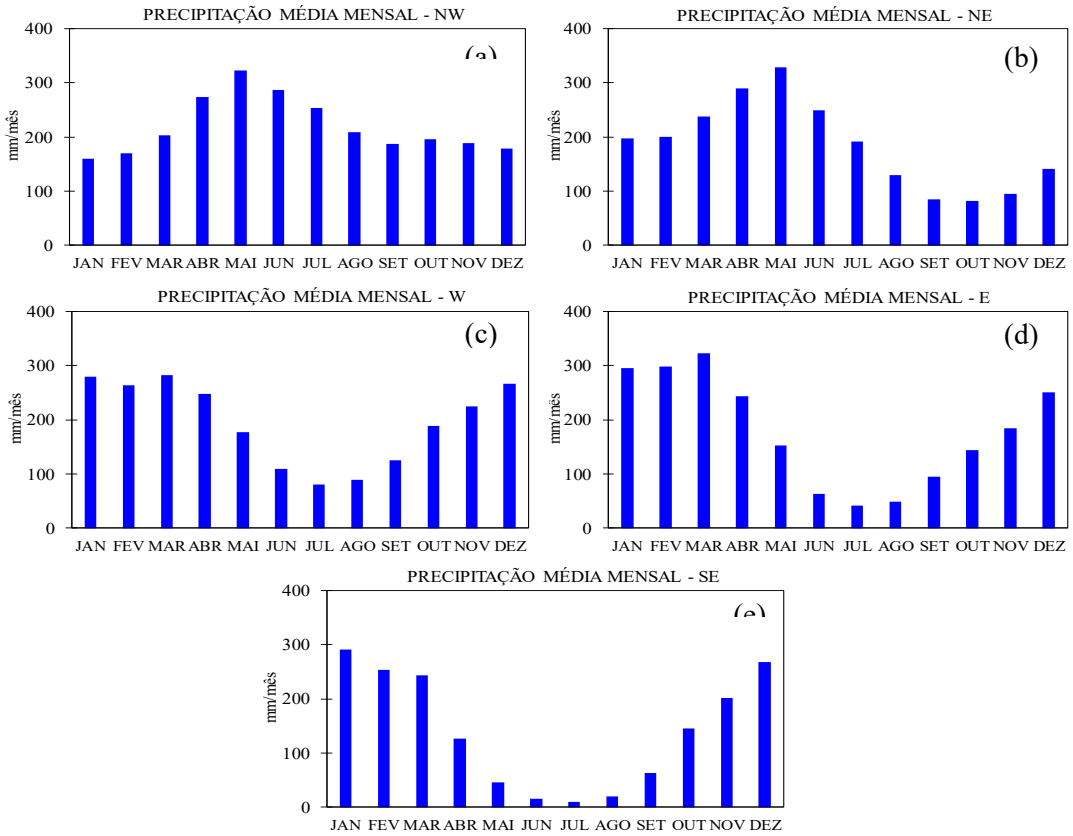
Figure 2 illustrates the precipitation climatology, averaged from 1981 to 2010, in the five sub-regions of the Amazon, highlighting the existence of spatial variations, with the highest accumulation in the NW (2,629 mm) and the lowest in the SE (1,685 mm). Figure 3 (a-e) shows the monthly climatology, highlighting distinct seasonal patterns: the NW and NE sub-regions have high rainfall throughout the year, without a well-defined dry season, despite the relative reduction between August and November. The peaks in May (323 mm in the NW and 328 mm in the NE) reflect the prolonged influence of the ITCZ in the northern Amazon (Rao; Hada, 1990; Ribeiro *et al.,* 2023). The reduction in precipitation in the second half of the year, although less intense than in the southern regions, maintains high volumes, suggesting the persistence of atmospheric humidity and the occurrence of local-scale meteorological systems (Souza *et al.*, 2021).

Figure 2 – Average annual rainfall (1981 to 2010) in the five sub-regions of the Amazon: Northwest (NW), Northeast (NE), West (W), East (E) and Southeast (SE)



Source: The authors (2025).

Figure 3 – Average monthly precipitation (1981 to 2010) in the five sub-regions of the Amazon: (a) Northwest (NW), (b) Northeast (NE), (c) West (W), (d) East (E) and (e) Southeast (SE)



Source: The authors (2025).

Although the climatology of precipitation has well-defined seasonal patterns in the Amazonian sub-regions, it was essential to investigate whether these regimes have been changing over time. The analysis of monthly precipitation trends across the entire time series allowed us to identify signs of changes in the region, in response to recent climatic and environmental factors, such as the influence of the ENSO phenomenon, for example. Figure 4 (a-e) presents the time series of monthly precipitation for the five sub-regions analyzed between 1979 and 2024, accompanied by their respective linear trend lines. The results indicate a statistically significant negative trend in precipitation across all sub-regions, as indicated by the slope coefficients of the simple linear regression equations (values of "b") and confirmed by Student's t-tests, with a p-value less than 0.05 in all cases (Table 1).

Table 1 – p-values of linear regressions applied to time series of monthly precipitation, rainfall extremes, and drought extremes in the sub-regions of the Amazon (1979 to 2024)

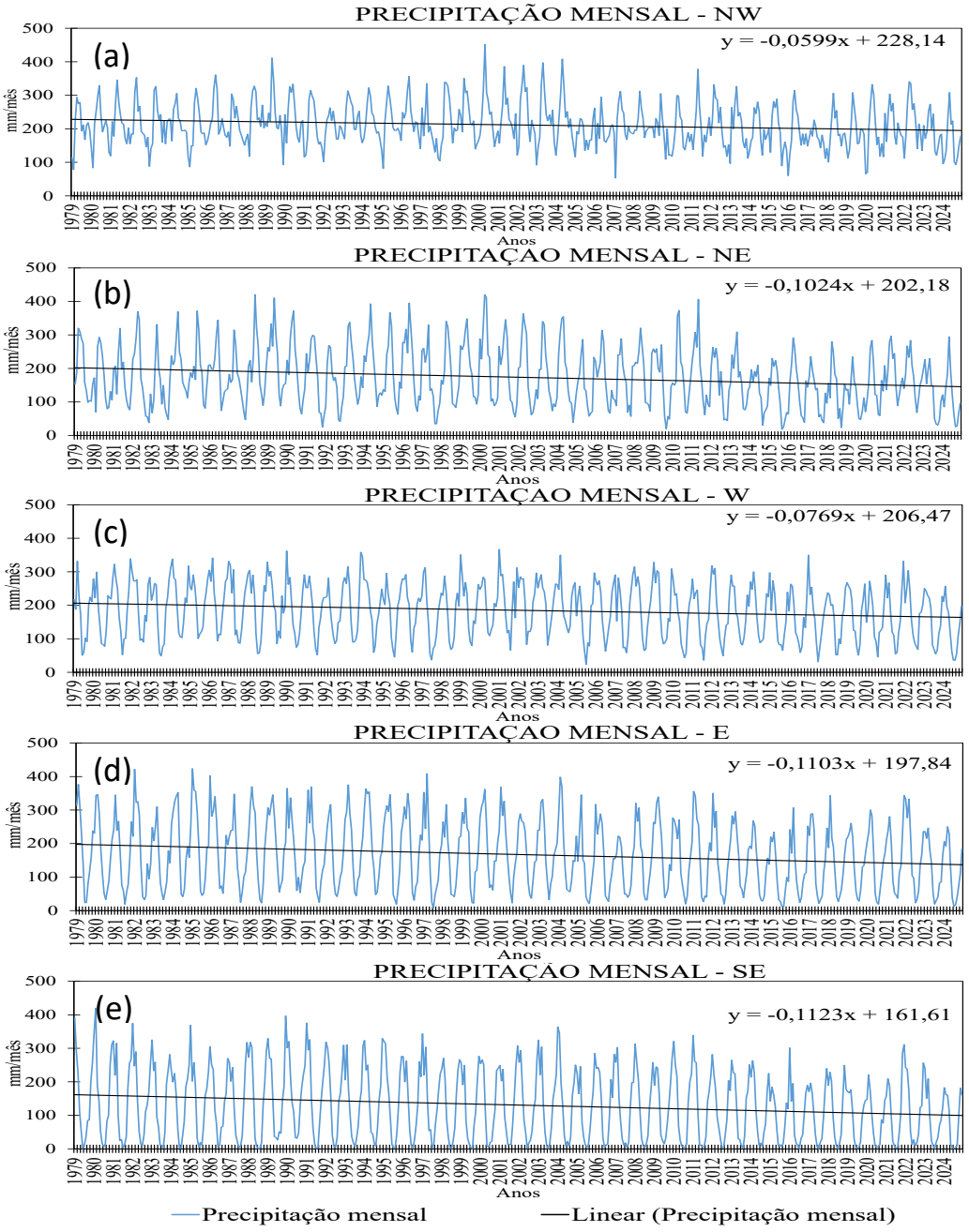
SUB-REGION	PRECIPITATION	EXTREME RAINY	EXTREME DRY
NW	0.012	0.052	5.760E-05
NE	0.000	0.088	8.556E-04
W	0.000	0.003	1.424E-03
E	0.000	0.000	1.716E-05
SE	0.000	0.000	1.186E-07

Source: The authors (2025). The significance level considered was p less than 0.05, indicating that the trend is statistically significant. Values less than 0.05 are shown in gray.

The NW sub-region showed an average decline of approximately -0.60 mm/month (y = -0.599x + 228.14), reflecting a gradual reduction in rainfall over the period, although this region still maintains high average monthly volumes, exceeding 300 mm during the rainy season months. The NE sub-region showed a more pronounced downward trend, with -1.02 mm/month (y = -1.024x + 202.18). Sub-region W recorded the lowest rate of reduction among the areas analyzed (-0.077 mm/month), on the other hand, sub-region E showed a reduction of -0.110 mm/month and the Southeast (SE) showed a decline of -0.112 mm/month (y = -0.1123x + 161.61), which is consistent with other studies that point to an increase in the dry season and intensification of extreme droughts in the southern part of the Amazon, especially in the transition to the Cerrado biome (Souza *et al.*, 2005; Marengo *et al.*, 2018). These results corroborate previous studies that show a trend of reduced rainfall in the Amazon in recent decades, especially in the eastern and southern portions, potentially associated with global climate change, the expansion of deforestation, and the feedback loop between loss of vegetation cover and reduced atmospheric humidity (Marengo *et al.*, 2011; Aragão, 2012).

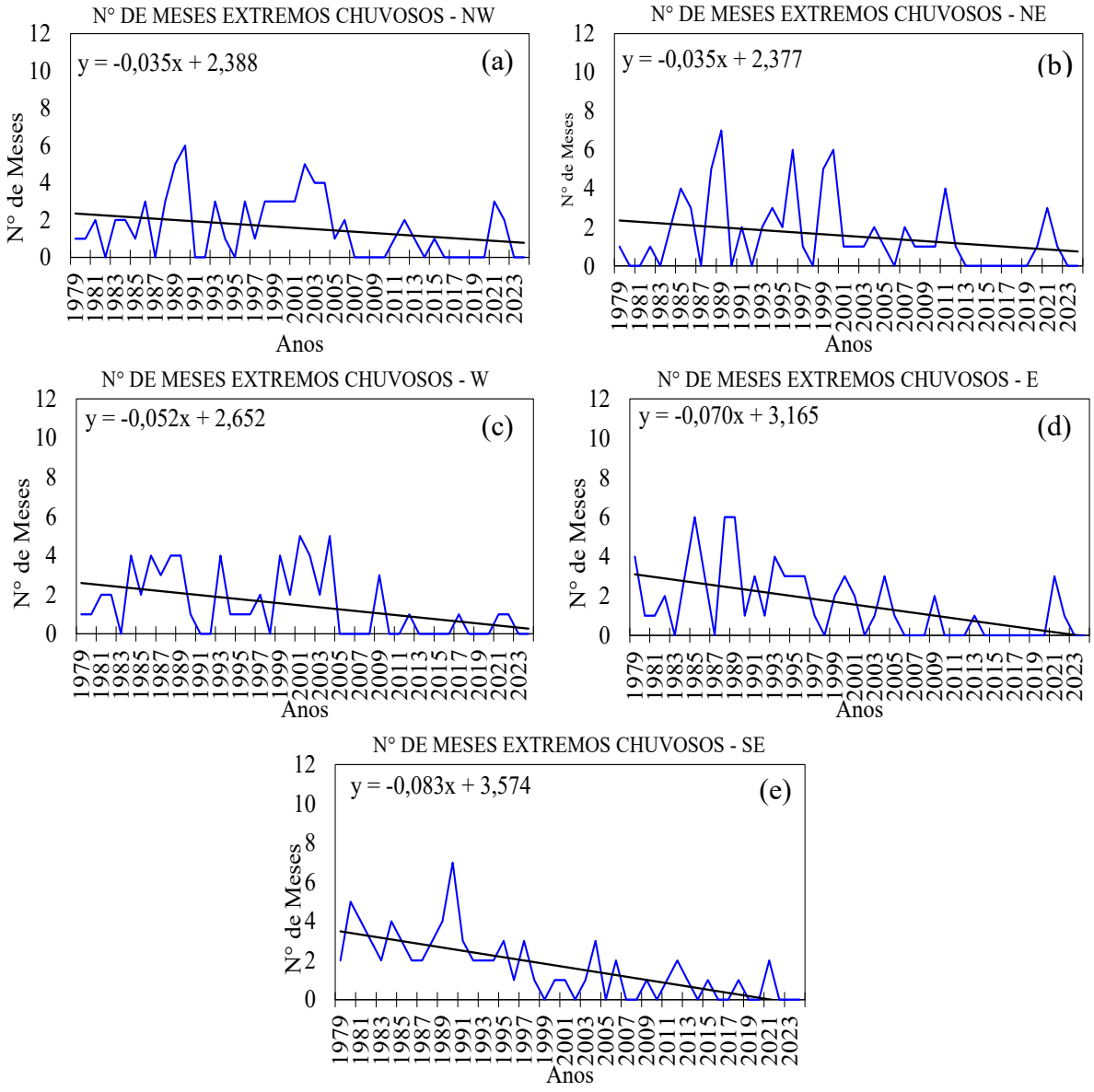
In addition to the trends of decreasing monthly precipitation totals observed in all Amazonian sub-regions, it is equally relevant to assess changes in the frequency of extreme events. These occurrences, often masked by climatological averages, have direct implications for water availability, river navigability, and the socio-environmental resilience of the region. Figure 5 (a-e) shows the trends in the annual number of months classified as extreme rainfall months, for the period from 1979 to 2024, in the five sub-regions of the Amazon. The results showed a predominance of negative trends in all areas, with varying magnitudes among the sub-regions. However, statistical significance tests (t) indicated that only the W, E, and SE regions showed statistically significant trends, while the NW and NE regions did not demonstrate significance, as can be seen in Table 1.

Figure 4 – Trend of monthly precipitation in the sub-regions of the Amazon (1979 to 2024). Monthly precipitation (blue lines) and respective linear trends (black lines) for the sub-regions: (a) Northwest (NW), (b) Northeast (NE), (c) West (W), (d) East (E) and (e) Southeast (SE)



Source: The authors (2025).

Figure 5 – Trend in the annual number of months with extreme rainfall events (above the 85th percentile) in the Amazon sub-regions: (a) Northwest (NW), (b) Northeast (NE), (c) West (W), (d) East (E) and (e) Southeast (SE), from 1979 to 2024. The black line represents the linear trend



Source: The authors (2025).

The NW and NE regions showed slopes of -0.035 events/year, with intercepts close to 2.4 annual events. Despite the visible negative trend, the absence of statistical significance suggests that interannual variability still predominates in the behavior of rainfall extremes in these areas. In the W, E, and SE sub-regions, the negative trend was more pronounced and statistically significant, with slopes of -0.052, -0.070, and -0.083 events/year, respectively. This suggests a consistent reduction in the frequency of extreme rainfall events in these areas,

possibly linked to the intensification of seasonal drought anomalies, the advancement of the dry season, and large-scale climate variability. The SE, for example, located in the transition between the Amazon and the Cerrado, showed the highest rate of decline, reinforcing evidence that this area is among the most sensitive to climate change (Souza *et al.*, 2005; Coe *et al.*, 2013).

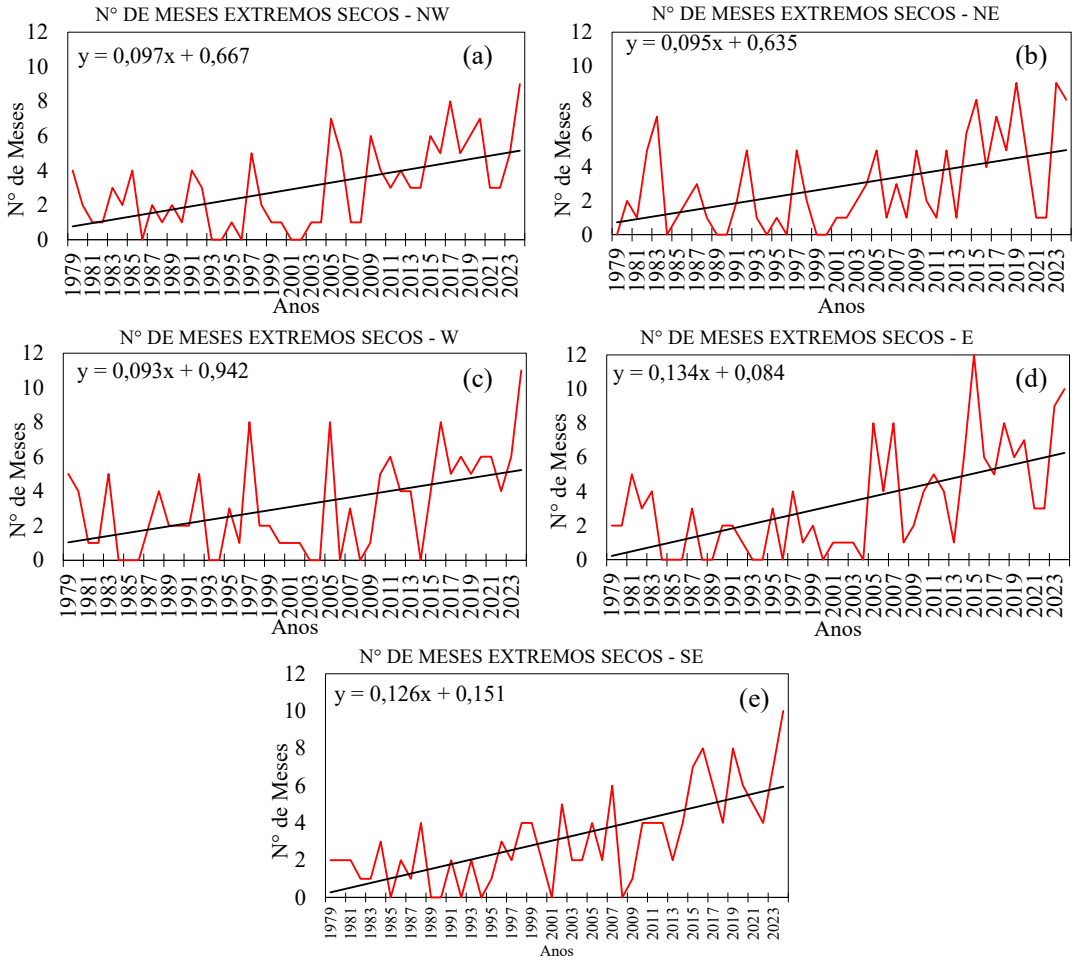
Analysis of extreme rainfall events indicates that the years 1989 and 1990 were the most significant in the NE, NW, E, and SE of the Amazon. In 1989, the frequency of months with extreme rainfall was highest in the NE (up to 7 months), as well as high in the NW and E, reflecting the strong influence of the 1988–1989 *La Niña* event, which intensified the ITCZ and increased moisture transport to the north of the region (Ronchail *et al.*, 2002). In 1990, the SE stood out, with up to 6 months of extreme events (Figure 5e), still under the residual influence of the previous *La Niña*, since, according to Silva and Silva (2015), there is a correlation between precipitation in the northern region of South America and sea surface temperature (SST) in the Equatorial Pacific, with a time lag. This means that atmospheric effects can persist even after the end of the oceanic event, due to the inertia of the large-scale circulation, which takes time to adjust to thermal variations in the ocean. This temporary decoupling between the ocean and the atmosphere contributes to prolonging the climatic impacts on tropical areas, such as the Amazon.

Figure 6 (a-e) illustrates the trends in the annual number of months classified as extremely dry (below the 15th percentile) for the period 1979 to 2024 in the five sub-regions of the Amazon. The results indicate an increasing trend in the number of months with extreme drought events in all sub-regions analyzed. The t-test confirmed that all trends are statistically significant, reflecting a consistent increase in the frequency of these events (Table 1).

The SE sub-region showed the highest annual growth rate (b = 0.126), followed by the E, NW, NE, and W regions, with b of 0.134, 0.097, 0.095, and 0.093, respectively, suggesting a systematic increase in the occurrence of severe droughts, which may be associated with changes in tropical atmospheric patterns and the impacts of global climate change (Coe *et al.*, 2013). The intensification of dry events has significant implications for the Amazon rainforest, which depends on a balanced hydrological cycle for its ecological maintenance. The increased frequency of dry months can intensify water stress in vegetation, reduce river flow, and increase susceptibility to forest fires, especially on the edges of the biome and in areas of deforestation and degradation (Aragão *et al.*, 2014; Souza *et al.*, 2003). Furthermore, the higher incidence of

droughts can compromise local livelihoods, river transport and the food security of traditional populations (Nobre *et al.*, 2016).

Figure 6 – Trend in the annual number of months with extreme dry events (below the 15th percentile) in the Amazon sub-regions: (a) Northwest (NW), (b) Northeast (NE), (c) West (W), (d) East (E) and (e) Southeast (SE), from 1979 to 2024. The black line represents the linear trend



Source: The authors (2025).

In general, the year 2024 was particularly critical for the NW, NE, E, and SE regions, with a high frequency of months experiencing extreme drought. Although this event is recent, preliminary research has indicated that the 2023-2024 drought in the Amazon was characterized by a combination of climatic factors, including *El Niño* and the anomalous warming of the North Atlantic, Indian, and North Pacific oceans. This combination significantly reduced precipitation and increased temperatures, affecting water availability, prolonging droughts, and causing temperature spikes (Marengo *et al.*, 2024).

Furthermore, the year 2015 stood out in sub-region E, where all 12 months recorded extreme dry values. This period coincided with one of the most intense *El Niño* events of the 21st century, as observed in the data from the Oceanic Niño Index (Alves, 2025). According to Marengo *et al.* (2018), the 2015 *El Niño* caused a significant reduction in rainfall in the Amazon region, with severe droughts between August and October, affecting ecosystems and hydrological regimes. The authors highlight that the combination of *El Niño* with local low humidity conditions resulted in one of the worst droughts observed in recent decades.

These results show that extreme drought events have become more frequent and widespread, especially in years strongly influenced by El Niño, reinforcing the importance of monitoring and adaptive management strategies in the face of increasing climate variability.

4 FINAL CONSIDERATIONS

Linear regression analyses applied to monthly precipitation series and the frequency of months with extreme precipitation (referred to as dry extreme and wet extreme) show statistically significant changes in the rainfall regime of the Legal Amazon in the period from 1979 to 2024. A generalized trend of reduction in total precipitation was observed in all sub-regions analyzed, with greater intensity in the E and SE sub-regions of the Amazon.

Particular attention should be given to the intensification of dry extremes, whose statistical sign

ificance was robustly verified in all sub-regions, with expressively low *p*-values, especially in the SE sub-region. This pattern suggests an increase in the frequency of severe drought periods, which has direct implications for water resource management, food security, and the resilience of Amazonian populations.

Although rainfall extremes show less statistical consistency in trends, some sub-regions, such as W and E, indicated significance in their regressions, pointing to a possible expansion of intra-annual precipitation variability. This behavior, coupled with the intensification of dry extremes, reinforces the scenario of increasing climate instability and a greater risk of natural disasters associated with both water scarcity and excess.

These results corroborate recent evidence in the literature on the impacts of climate change in the Amazon and highlight the urgency of strengthening climate monitoring strategies, territorial planning, and integrated public policies, focusing on risk mitigation and adaptation to the new hydrometeorological conditions of the region. The statistical characterization of

extreme rainfall trends is, therefore, an essential tool for the sustainable and sovereign management of the Amazon in the face of the challenges posed by global changes.

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Policy Papers

Propositional in nature, this section presents policy papers that discuss the implications of climate change for Amazon security and defense, offering recommendations to the Brazilian State, particularly to the Defense sector. In this edition, three texts are presented which, from different perspectives, address the challenges and opportunities related to the sovereign and sustainable management of the Amazon.

The paper *"Impacts of climate change on Amazon security and defense: a strategic analysis"* addresses the intersection between the climate agenda and national security, analyzing how climate change amplifies vulnerabilities and instabilities in the region. According to the text, mitigating these challenges requires a set of measures, ranging from strengthening the State's response capacity to enhancing international cooperation.

In *"Oil exploration in the Brazilian Equatorial Margin and its impacts on National Defense,"* the implications of oil exploration in the Equatorial Margin for national defense are examined, addressing geopolitical, environmental, and energy-related aspects. The analysis considers the role of the Armed Forces in regional security and presents recommendations to mitigate risks and maximize opportunities for sovereign and sustainable development.

Finally, *"Management of Recyclable Waste in the Brazilian Army: implementation of Selective Collection"* describes the Citizen Selective Waste Collection Program, a solid waste management policy that has generated environmental and social benefits while fostering the circular economy. Focusing on activities carried out within Brazilian Army units, the text discusses challenges related to expanding partnerships, strengthening institutional capacity, and overcoming logistical constraints within the scope of Defense activities.

Impacts of climate change on the security and defense of the Amazon: a strategic analysis

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Executive Summary

This Policy Paper addresses the growing relevance of the intersection between the climate agenda and national security, focusing on the implications for the Brazilian Amazon. The region, vital for regulating the global climate and possessing vast natural resources, faces complex challenges stemming from extreme weather events, increased deforestation, and pressures on its resources. The upcoming COP30, to be held in Belém, Pará, in 2025, intensifies the urgency of debating environmental securitization and the need for coordinated actions to mitigate climate risks. The study analyzes how climate change amplifies vulnerabilities and instabilities in the Amazon, impacting food security, water availability, and political stability. Environmental degradation, driven by illegal activities such as mining and logging, exacerbates the situation, jeopardizing the biodiversity and ecological balance of the region. The analysis also considers the implications for national security, including regional instability, population displacement, threats to strategic infrastructure, and the intensification of cross-border criminal activities. Given this scenario, the objective of this work is to present general recommendations that will strengthen security and defense conditions in the Brazilian Amazon. The text structure comprises a detailed analysis of the problem, followed by a set of practical and feasible recommendations, based on the evidence that was the subject of research.

The main recommendations include: 1) strengthening the State's capacity to respond to extreme weather events; 2) investing in technologies for monitoring and combating environmental crimes; 3) promoting sustainable development policies; 4) integrating climate considerations

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into national security and defense planning; and 5) strengthening regional and international cooperation for the protection of the Amazon.

Implementing these measures is essential to guarantee national sovereignty, the security of the population, and the preservation of the Amazon's environmental heritage, in the context of growing climate challenges, which are increasingly taking on geopolitical dimensions.

Keywords: climate security; Amazon; national security; sustainable development; securitization.

1 THE DYNAMICS OF THE CLIMATE ISSUE IN THE AMAZON

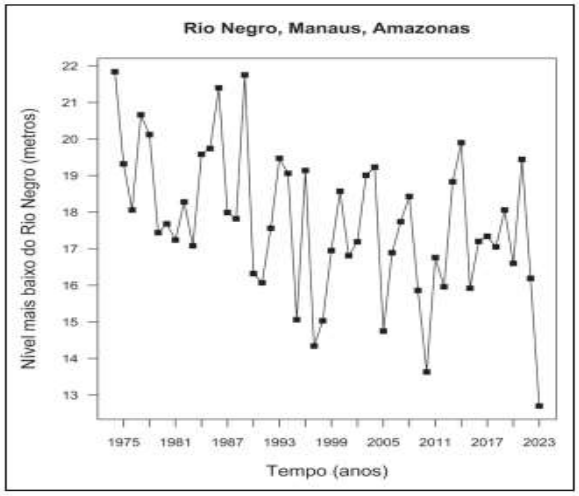
The Brazilian Amazon has faced increasing challenges related to climate change. The constant increase in average temperature, the occurrence of extreme weather events, the increase in deforestation and wildfires, and the pressure on existing natural resources in the region are obstacles that need to be prevented or combated.

Even though extreme weather events occur naturally, their frequency and intensity have increased significantly in recent times. In the Amazon, more frequent, intense, and prolonged episodes of drought have been observed, negatively impacting biodiversity, human health, and food security in the region (IPCC, 2023). Similarly, floods have been occurring more frequently, causing destruction in riverside communities and affecting local infrastructure (Marengo *et al.*, 2018).

The Amazon River basin presents conditions for human occupation that are susceptible to the consequences of extreme events generated or aggravated by climate change. In 2023, acute rainfall conditions at the beginning of the year caused exceptional floods in the states of Acre, Amazonas, Pará, and Maranhão, forcing 116,000 people to leave their homes (IDMC, 2024 *apud* Mendes and Spécie, 2024).

Also in 2023, starting in the middle of the year and continuing throughout the second half, the same region was plagued by drought, especially the state of Amazonas, which experienced the worst drought in a century. The Amazon River and its largest tributary, the Negro River, have reached their lowest recorded water levels, with devastating consequences for the fauna and vegetation (Figure 1). Riverside communities and indigenous groups were affected, and thousands of people migrated (INMET, 2023; NASA, 2023; FAPESP, 2023 *apud* Mendes and Spécie, 2024).

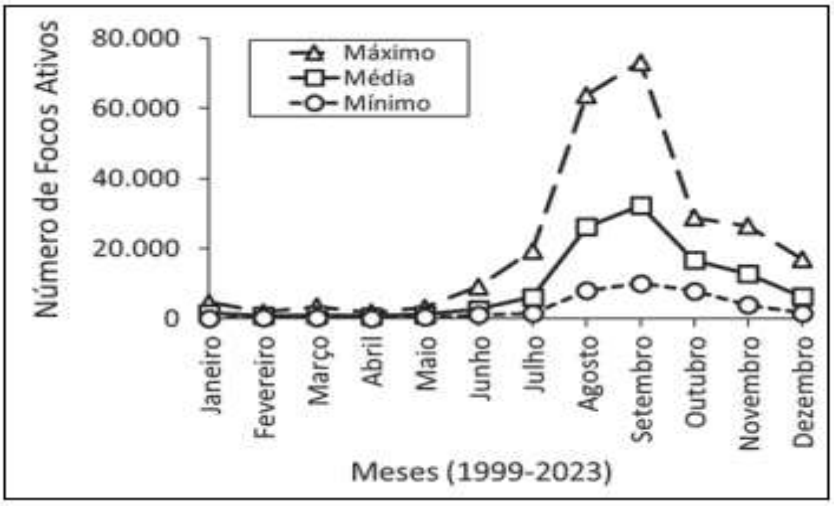
Figure 1 – Representation of the minimum (low) level of the Rio Negro (1974-2023)



Source: Brandão *et al.*, 2024.

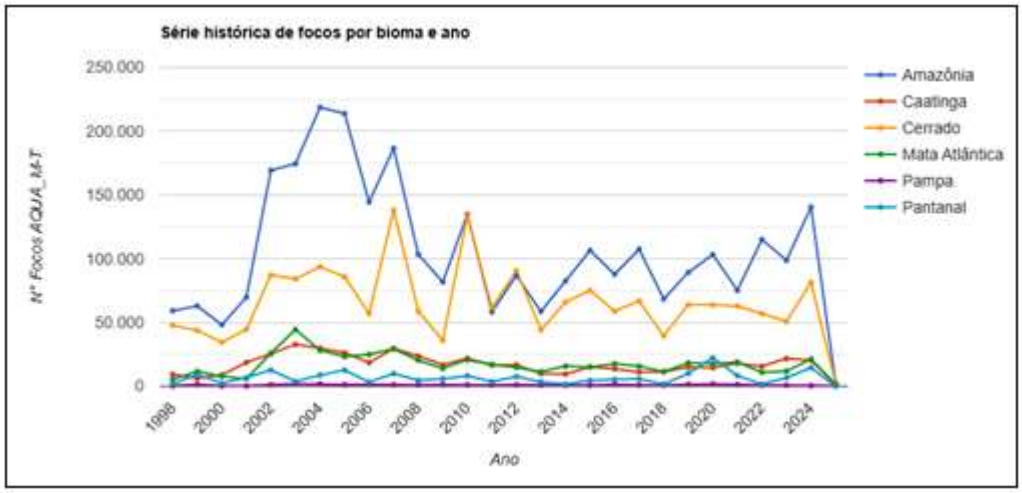
Benefiting from the aforementioned climatic conditions, which tend to worsen in the months of August, September, and October (Figure 2), anthropogenic actions of environmental degradation place more pressure on policies for the preservation of the Amazon. Based on data from the National Institute for Space Research (INPE), it appears that the Amazon biome is, in recent history, the Brazilian biome most subject to the occurrence of fire outbreaks (Figure 3).

Figure 2 – Comparison of maximum, average, and minimum values of active fire outbreaks (1999-2023), according to data from the AQUA_M-T satellite



Source: Brandão *et al*. (2024), based on data from INPE (2024).

Figure 3 – Comparison of current year data with maximum, average and minimum values between 1998 and April 16, 2025



Source: INPE, 2025.

According to Barlow and Peres (2008), the combination of droughts and forest fires increases tree mortality two to four times in the Amazon, which may be related to a severe modification in the physical structure of the forest, as well as a significant reduction in the number of native species. In this context, Table 1 shows how pressure on native vegetation has recently shown a growing trend.

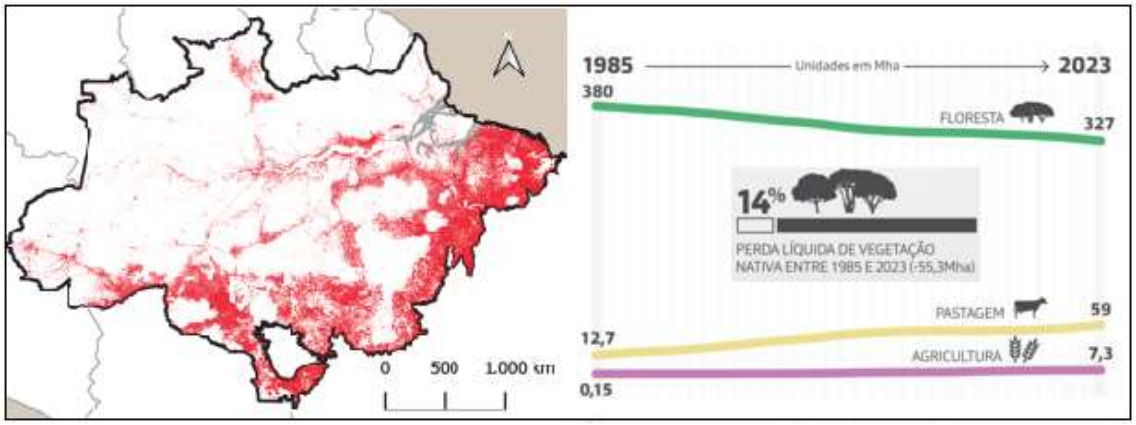
Table 1 – Percentage of fire outbreaks in native vegetation areas in the Amazon (2019-2024)

2019	2020	2021	2022	2023	2024	Average
11.8%	12.3%	9.1%	9.8%	12.2%	22.3%	13.6%

Source: The author, based on data from INPE (2025).

In this context, one of the conditions related to this phenomenon is the recent expansion of agribusiness frontiers in the country, which has been advancing on the fringes of the Legal Amazon, as stated by Pereira *et al.* (2020) (Figure 4).

Figure 4 – Accumulated deforestation in the Amazon (2022) and annual evolution of land use (1985-2023)



Source: The author, based on Brandão *et al.* (2024) and MapBiomas (2025).

Another very particular (and lucrative) constraint on the Amazon relates to the exploitation of mineral resources in its soil. Data from 2023 reveals that the Amazon concentrates 69.7% of the mining areas in the country, which includes industrial mining and artisanal mining, with the latter being more prevalent, totaling 306,918 hectares (Mapbiomas Brasil, 2025).

The issue of illegal mining in the Amazon region is particularly worrying. This is a small-scale mineral extraction activity, often carried out by individuals or small cooperatives, with low investment in technology and infrastructure. Thus, illegal mining is projected as an undertaking with a disproportionately large environmental impact, given its often predatory and unregulated practices (Boehm, 2024).

In the Amazon, illegal mining has a high rate of illegality and is frequently associated with local socio-environmental conflicts, such as illegal deforestation, pollution of water sources, child prostitution (Pinto and Vieira, 2018), and drug and arms trafficking. infantil (Pinto e Vieira, 2018) e o tráfico de drogas e armas. It is worth noting that, of the area mined in the Amazon, 10% is located within indigenous territories. The Kayapó, Munduruku, and Yanomami indigenous lands are the most occupied by illegal miners, concentrating 90% of the mined area located in lands of this category. (Boehm, 2024).

All of this has led recent research to focus on what has been called the “tipping point”. This refers to a condition in which there would be an irreversible reduction in biological diversity and forest carbon stocks, triggered by hydrological and energy changes resulting from the pace of global climate change and land use in the region. As a result, there would be a

process of *savannization* of the Amazon (Nobre *et al.*, 2023). Estimates indicate that, by 2050, between 10% and 47% of the Amazon rainforest could reach this critical point (Flores *et al.*, 2024).

Thus, the climate issue has an inseparable relationship with the Amazon. From this, socio-environmentally conflicting conditions are created, which may reveal serious challenges to national security.

2 THE EMERGENCY OF CLIMATE SECURITY AND ITS IMMPACTS ON THE AMAZON

The upcoming 2025 United Nations Climate Change Conference, COP30, in Belém, intensifies the relevance of the intersection between climate change and the challenges facing the Amazon on the global environmental agenda.

Previous editions of COP have not shied away from debating the topic and, therefore, serve as a prelude to what will be discussed in the 2025 edition. COP26, for example, held in Glasgow in 2021, brought to the forefront discussions about the importance of the Amazon for global climate security. In it, among the various debates, a Scientific Panel for the Amazon was established, which released a report warning that the forest was close to a critical point in more than 60% of its basin (Modelli, 2021).

At COP27 in 2022, held in Sharm El Sheikh, Egypt, President Luiz Inácio Lula da Silva, in his speech, emphasized the fundamental role of the Amazon for humanity, saying that: "There is no climate security without a protected Amazon," in a clear attempt to draw the world's attention to the need to create financial mechanisms to remedy losses and damages caused to the Amazon due to climate change (Lima, 2022).

In this context, a better understanding of what two very useful terms for the discussion at hand can represent is needed: climate security and environmental securitization.

According to the International Organization for Migration (2025), a United Nations agency working in the field of migration and climate security

> refers to the direct and indirect impacts of the climate crisis on peace and security, where climate change acts as a threat multiplier, exacerbating underlying vulnerabilities and compounding existing grievances. The consequences of climate change affect all areas of human security (economic, food, health, environmental, personal, community and political) and undermine conflict prevention, sustaining peace and sustainable development efforts with a disproportionate impact on communities with existing vulnerabilities [...].

In turn, the Pacific Northwest National Laboratory (2025), a laboratory affiliated with the United States Department of Energy, presents a broader definition, but one that follows a similar logic, stating that:

> Climate security represents the physical, economic, or societal impacts associated with climate change that substantially alter political stability, human security, or national security infrastructure The escalating climate crisis generates geopolitical and socioeconomic stressors, such as population displacement, terrorism, economic stagnation, infrastructure impacts, and social unrest.

Therefore, the Brazilian Amazon, being the largest tropical rainforest biome in the world, is recognized as crucial to global climate security. According to Nobre *et al.* (2023),

> The Amazon rainforest is essential for regulating the global climate, acting as a carbon sink and contributing to the hydrological cycle. Degradation and deforestation of the Amazon could have devastating consequences for the planet's climate security.

This opens the door for the construction of narratives that reinforce positions of environmental securitization. Environmental securitization is a theoretical concept from the field of strategic studies. It develops from the dialogue between the currents of Structural Realism and Wendtian Constructivism and refers to the process by which environmental issues are elevated to the level of a threat to national or international security, thus justifying the use of extraordinary measures for their resolution (Buzan *et al.*, 1998).

Securitization, according to Buzan *et al.* (1998, pp. 23-24), occurs "(...) when an issue is presented as an existential threat, requiring emergency measures and justifying actions outside the normal bounds of political procedures."

This type of strategic conception became very common after the Cold War, driven by the success of the Copenhagen School, which led many international agendas to address issues that were not previously viewed from a security perspective. Issues such as the economy, human rights, and the environment have become security matters and have come to be treated as a priority. In addition, new reference objects (i.e., things that are under threat) have gradually been perceived as eligible for protection by the international community (Mendes *et al.*, 2020).

Therefore, the securitization of the Amazon can lead to an increase in regional and international cooperation mechanisms, as in the cases of the Amazon Cooperation Treaty Organization (ACTO) and the Amazon Fund, but it can also result in tensions between States, especially if strategic resources such as water and energy are in dispute.

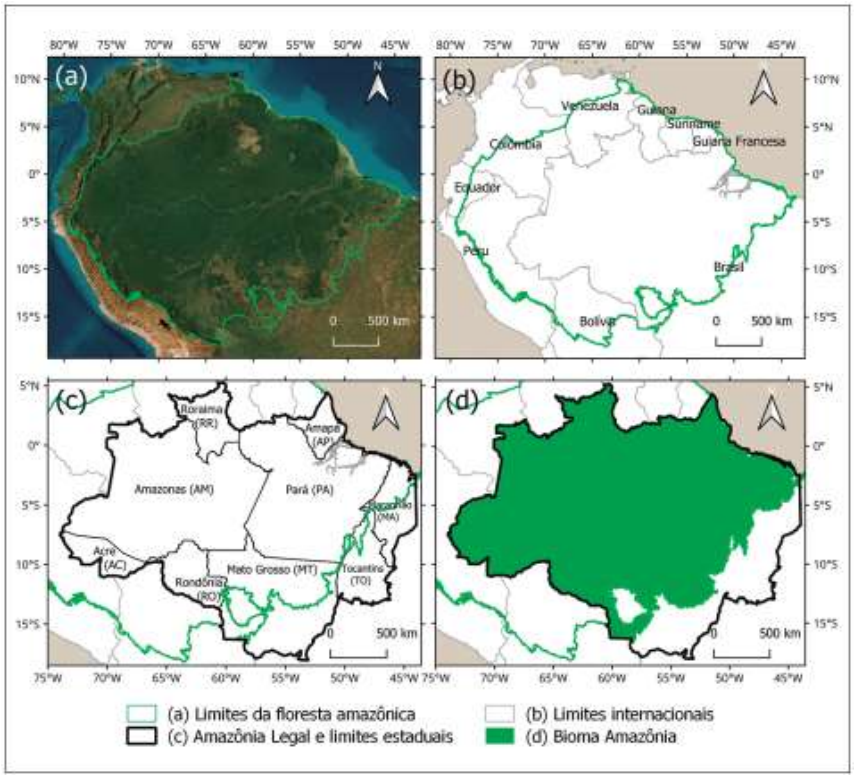
3 IMPLICATIONS OF CLIMATE CHANGE IN THE AMAZON FOR BRAZIL'S SECURITY AND DEFENSE

From what has been presented so far, it can be inferred that, in contemporary times, climate issues will always have an impact on matters related to National Security. When such issues are focused on the Brazilian Amazon, their impacts take on superlative dimensions, given the geostrategic nature of this region for the country and its relevance to global climate regulation, granting it a double value, from both a domestic and international perspective (Mafra, 2006).

The importance of the Amazon for Brazilian national security is highlighted by Professor Therezinha de Castro, who, in her extensive work on the subject, emphasized the need to integrate the region into the national whole to guarantee the country's sovereignty and its sustainable development. Therefore, within the idea of "integrating so as not to surrender," that renowned geopolitical theorist advocated for an integrated approach that combined economic development, environmental protection, and territorial defense, in order to guarantee the security and prosperity of the Amazon (Mafra, 2006).

The Brazilian Amazon, in addition to covering approximately 60% of Brazilian territory, shares 11,000 km of borders with seven countries: Venezuela, Guyana, Suriname, French Guiana (a French overseas territory), Colombia, Peru, and Bolivia. Furthermore, it patents for itself full control of the mouth of the Amazon, the gateway to the exploitation of much of the biome's potential, which includes the largest reserves of surface and groundwater in the world: the Amazon basin and the Great Amazon Aquifer System (Figure 5) (Abreu *et al.*, 2013 *apud* Peixoto Júnior, 2020).

Figure 5 – Geospatial delimitation of the Amazon area



Source: Brandão *et al*. (2024), based on data from INPE (2023); QGIS (2023).

In this context, the low human occupation rates in the Amazon (Viana, 2021) are compounded by the mobility difficulties in that area, which are exacerbated by dissociative forest assets and by sparse and poorly structured road networks (Virga *et al.*, 2021). This combination of factors results in regional socioeconomic asymmetries (Viana, 2021), which then point to the need for a geopolitical guideline structured around the need to integrate the region into the national whole, which involves initiatives by the public authorities, such as the technical development of indigenous populations, in order to promote social well-being, accompanied by the sustainable exploitation of the natural resources richly offered by the Amazon (Mafra, 2006).

For all these reasons, perhaps no other part of Brazil can translate the validity of the trinomial Security, Development and Defense as well as the Amazon. In this region, the parts of this trinomial assume interdependent concepts, without which one cannot develop without the other.

In this context, Security is a duty of the State and can be understood as an indispensable "factor of production" for Development, guaranteeing it the necessary stability. Development, in turn, ensures that the State has the resources necessary to promote its own Security, being

able to protect its people and institutions against all sorts of threats (Arruda, 1989). From this mutually supported interaction, the result is the strengthening of the country's Defense capacity, through its ability to mobilize resources for the Nation's struggle and resistance in favor of guaranteeing its sovereignty (Couto and Silva, 1967 *apud* Mansan, 2022).

Therefore, it can be inferred that the development of sustainable production chains in the Amazon can generate employment and income for local communities, reduce pressure on natural resources, and strengthen the State's presence in the region, developing a healthy socio-bioeconomy that benefits from the entire ecosystem through an interdisciplinary economic approach. This may include forest restoration and conservation; agroforestry system management; industrial processing of native products; sustainable extraction of mineral resources; fisheries management; ecotourism; and biotechnology development (Brandão *et al.*, 2024).

National Security, then, under the understanding of the trinomial Security, Development, Defense already presented, would translate into the relative guarantee that the State provides to the Nation, using its resources, in order to achieve and preserve its Fundamental Objectives: sovereignty, democracy, social peace, national integration, progress and the integrity of the national patrimony (Escola Superior de Guerra, 2024).

Therefore, based on the understanding of National Security and through the conjunction of the influences of the climate agenda on the Amazon, the implications of the topic under study for Security and Defense issues can be objectively determined, namely:

a. Regional instability and population displacements: climate migrations in the Amazon can generate social tensions and conflicts over resources, both local and transnational, requiring a response from the State to guarantee the security and stability of affected areas.

b. Threat to strategic infrastructure: following the occurrence of extreme events, the perceived risk to regional infrastructure increases. This includes the operation of roads, ports, and other essential logistics or service facilities located in the Amazon.

c. Intensification of illegal activities of a local and cross-border nature: environmental degradation and biodiversity loss, exacerbated by climate change, can increase pressure on the Amazon's natural resources, encouraging illegal activities such as biopiracy and illegal mining. Such activities are facilitated by border and local landlocked communities.

d. Need for adaptation, training, and equipping of the State's defense, security, and oversight apparatus for future (and present) challenges: security forces and the Armed Forces need to be able to work in the unique environment of the Amazon rainforest, as it is and as it

may become. This includes training personnel to operate in extreme weather conditions and the use of advanced technologies.

e. Need for regional and international cooperation: the protection of the Amazon must be a shared responsibility, since the Amazonian biome transcends national borders and its scientific and environmental value is recognized by the international community.

4 RECOMMENDATIONS

The climate agenda poses internal and external challenges to the Amazon. These challenges are multifaceted and complex, requiring the mobilization of all expressions of National Power (Political, Economic, Psychosocial, Military, and Scientific-Technological).

In this sense, a national debate regarding broader strategic directions that could safeguard national assets in that region becomes imperative. There is a clear vicious cycle in which internal factors, such as demographic voids and the inadequacy of the state control apparatus, combine in an entropy of forces that limit the sustainable development of the Brazilian Amazon, giving substance and supposed legitimacy to external interferences, which are often accompanied by Balkanizing[1] intentions and theses of limited sovereignty over an area of global relevance.

Therefore, it is necessary, and urgently, to develop a multidisciplinary political-strategic approach that takes into account the following recommendations:

.The State needs to be prepared to deal with the increase in migratory flows and the protection of vulnerable populations, coordinating humanitarian assistance and order maintenance actions, with flexibility and adaptability, in order to mitigate the formation of regional instability zones.

.The State must invest in resilient infrastructure and contingency plans that guarantee the operability of essential services to the local population, the maintenance of road communication lines and the capacity to respond to emergencies, thus preserving its strategic structures.

[1] The term refers to a process of **territorial and political fragmentation** to which a geographic area can be subjected. In this context, the area is divided into smaller entities, often hostile to each other or susceptible to external influences, resulting in instability and loss of central control, as occurred with the former Yugoslavia in the Balkans. In the case of the Amazon, it is suggested that the same phenomenon could occur if Brazilian indigenous policy, particularly when dealing with the demarcation of indigenous lands, disregards geopolitical and strategic analyses crucial to the country's security and defense.

.The Armed Forces and security, inspection, and control agencies need to intensify monitoring and surveillance at the borders and in critical areas of the Amazon, in order to prevent and combat the occurrence of illegal activities that weaken National Security.

.The State must invest in specialized training and new technologies, including defense systems geared towards anti-access and area denial (A2/AD), telecommunications systems, remote sensing, and climate modeling, in order to deter threats and strengthen its response capacity.

.The State must promote cooperation with other countries, in order to facilitate the sharing of information, coordinate preventive and repressive actions of a combined nature, and seek resources or partnerships that provide opportunities for the sustainable development of the region.

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Oil exploration in the Brazilian Equatorial Margin and its impact to the National Defense

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Executive Summary

The Brazilian Equatorial Margin, which stretches from the coast of Rio Grande do Norte to Amapá, has a high potential for oil exploration, estimated at billions of barrels of oil. However, its exploration raises critical points related to national defense, involving discussions about the protection of sovereignty, energy security, and environmental preservation. The region is situated within two fundamental strategic domains: the Legal Amazon and the Blue Amazon, both targets of external threats and internal vulnerabilities that demand integrated and effective public defense policies. The oil exploration on the Equatorial Margin requires increased monitoring of offshore infrastructure, i.e., marine environments, prevention of environmental threats, and strengthening sovereignty over the continental shelf. The growing presence of foreign vessels and illegal activities in the region also increases the need for surveillance and cooperation between defense and security agencies. In the context of the Legal Amazon, oil exploration can generate environmental impacts in sensitive biomes, affecting traditional populations and essential water resources. Furthermore, there are concerns regarding international pressure and potential sanctions should there be failures in the environmental management of the activity, which requires a strong diplomatic stance from Brazil. In the Blue Amazon

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region, energy security takes center stage, given that exploration in the Equatorial Margin can reduce dependence on imports and strengthen the country's energy autonomy. However, protecting offshore platforms against cyberattacks, environmental accidents, and acts of sabotage becomes a key challenge for the Ministry of Defense. This policy paper examines the implications of oil exploration in the Equatorial Margin for national defense, addressing geopolitical, environmental, and energy aspects. The analysis considers the role of the Armed Forces in the region's security and presents recommendations to mitigate risks and maximize opportunities for sovereign and sustainable development. Among other measures, the proposal includes strengthening the military presence in the region, developing and improving infrastructure for responding to environmental emergencies, strengthening governance, particularly in energy security policy, and improving Brazil's diplomatic strategy in the sector.

Keywords: equatorial margin; oil and gas; energy security; environmental management; Amazon.

1 OIL AND GAS IN THE EQUATORIAL MARGIN

The Brazilian Equatorial Margin is a coastal strip located in the north and northeast of the country, encompassing the coastal area between the states of Amapá and Rio Grande do Norte. As can be seen in Figure 1, this region includes five sedimentary basins of great importance: The Amazon River mouth, Pará-Maranhão, Barreirinhas, Ceará, and Potiguar regions are all recognized for their significant potential for oil and natural gas exploration (INSTITUTO BRASILEIRO DE PETRÓLEO, 2025).

From a geopolitical and environmental perspective, the Equatorial Margin occupies a unique position, as it is located at the confluence of two strategic spaces for Brazil: the Legal Amazon, in the continental territory, and the Blue Amazon, which includes the territorial sea, the exclusive economic zone (EEZ) and the extended continental shelf in the Atlantic. In this context, potential oil and gas exploration and production activities in the Equatorial Margin raise debates about possible impacts on both the Amazonian biome, recognized for its biodiversity and global climate relevance, and marine ecosystems. Such discussions remain open, pending in-depth technical studies to assess the extent and nature of these effects. Although there is no consensus on the magnitude of these potential impacts, the issue is relevant because it involves not only

environmental preservation, but also national sovereignty over sensitive natural resources.

In recent years, the region has attracted increasing interest from energy companies and the Brazilian government, motivated by geological characteristics similar to those observed in the basins of Guyana and Suriname, countries that together have already identified reserves exceeding 13 billion barrels of recoverable oil (SERVIÇO GEOLÓGICO DO BRASIL, 2024), which refers to the volume of oil that can be extracted from an underground reservoir in an economically viable way and with the available technology. Preliminary studies by the Energy Research Company (EPE) indicate that the Amazon River mouth has similar conditions, with approximately 6.2 billion recoverable barrels, which reinforces expectations regarding its productive potential (EPE, 2024).

Figure 1 shows the location of this region, presenting the basins of the Brazilian Equatorial Margin.

Figure 1 – Basins of the Brazilian Equatorial Margin

Source: Antunes (2023).

In addition to the possibility of significantly expanding national oil and gas production, exploration in the Equatorial Margin represents an opportunity to strengthen the country's energy security, reduce dependence on imports, and generate economic development in the North and Northeast regions. However, this progress also brings

significant challenges, both from an environmental standpoint – given the sensitivity of the ecosystems involved – and in terms of governance, oversight, defense, and protection of critical infrastructure associated with the energy production chain.

According to some entities and organizations, oil exploration on the Equatorial Margin involves significant environmental risks, especially due to the proximity of areas of high biodiversity, such as Amazonian reefs, estuaries, and mangroves, which play a crucial role in climate regulation and the maintenance of ecosystem services. News has been circulating regarding possible accidents, such as oil spills, that could cause irreversible impacts on marine fauna, coastal communities, and the biomes of the Blue Amazon and the Legal Amazon themselves (Associação[...], 2025; WWF BRAZIL, 2023).

Cordeiro's work (2023), which analyzed a series of environmental studies prepared within the scope of environmental licensing processes for exploratory oil activity in the equatorial margin basins, indicates that, although the projects analyzed are located in areas distant from the coastline, the zones of influence associated with drilling activities can cover tens of kilometers and reach several coastal municipalities. The analysis of potential impacts in accidental scenarios revealed the possibility of effects that extend beyond the limits of national jurisdiction, with the potential to reach the territories of neighboring countries.

In geopolitical terms, the intensification of resource exploration in the equatorial margin entails risks to national sovereignty, especially given factors such as increased maritime traffic, the heightened interest of foreign actors in strategic resources, and the vulnerability of critical offshore infrastructure, which may be targeted by cyberattacks, sabotage, or transnational crimes.

Although it is impossible today to accurately determine the occurrence of these risks, there are precedents and technical and academic literature that demonstrate how similar scenarios have already been considered in other contexts: for example, the U.S. Government Accountability Office report (United States, 2022) on cyber risks to offshore oil infrastructure, as well as the study by Kashubsky (2011), which shows how oil platforms are considered attractive targets for attacks due to their potential for damage in different areas. These cases reinforce the idea that, even if only speculatively, such risks are legitimate and require the Brazilian State to proactively consider strengthening its presence and coordination between the defense, environmental enforcement, and active diplomacy sectors.

Thus, the country's strategic robustness depends on policies and capabilities that anticipate threats and preserve sovereignty over the Blue Amazon and the Brazilian jurisdictional waters.

Discussions regarding oil exploration in the equatorial margin require an integrated approach that combines rigorous environmental criteria and effective governance mechanisms in order to mitigate risks and maximize economic and social benefits. In this context, it becomes necessary to assess its implications for national defense, especially with regard to defense capabilities and the protection of Brazil's sovereignty.

2 IMPLICATIONS FOR THE DEFENSE

Oil exploration in the Equatorial Margin poses substantial challenges to the security and defense of Brazilian territory, especially regarding the protection of offshore infrastructure, maritime traffic, and the logistics chains involved in oil production and distribution. The growing presence of foreign vessels in the region, whether for commercial interests, illegal fishing, or other possible unauthorized exploitation of natural resources, requires strengthened surveillance and constant monitoring by the Armed Forces.

Defending Brazil's continental shelf and exclusive economic zone has become a strategic imperative, requiring investments in modernizing the Brazilian Navy's fleet, expanding its network of radars and sonars, integrating satellite surveillance systems, and strengthening the patrolling and rapid response capabilities of the Armed Forces. Furthermore, the need for protection against cyber threats is growing exponentially, given that attacks on control systems of offshore platforms could compromise production and generate severe environmental impacts. The remote location in deep waters, coupled with the need for real-time monitoring and control, means that offshore oil and gas assets potentially present a wider attack surface compared to other subsectors of the industry. This factor is particularly relevant considering that offshore production accounts for approximately 30% of global oil and gas production (Mohammed *et al.*, 2022).

Another aspect relevant to national defense is the intersection between energy security and territorial security. Increased exploration in the Equatorial Margin could help ensure the maintenance of independence from oil imports, making Brazil less vulnerable to fluctuations in the international market. Furthermore, the Ministry of Mines and Energy

points out that exploration in the region is essential to prevent Brazil from becoming dependent on oil imports again, ensuring energy security and boosting economic development (Brasil, 2025). However, the geographical location of this activity in a maritime border region reinforces the importance of a robust defense policy, focused on protecting critical facilities and ensuring the continuity of operations.

At the same time, oil exploration in this region demands greater cooperation between different government agencies, including the Navy, the Air Force, the Army, the Management and Operational Center of the Amazon Protection System (Censipam), the Federal Police, and the Brazilian National Petroleum Agency (ANP). Creating joint operational protocols and conducting incident response simulations, such as for oil spills or sabotage attempts, are necessary measures to ensure operational readiness.

Economic activity in the Equatorial Margin also impacts maritime security and requires a greater state presence to guarantee sovereignty and control over Brazilian jurisdictional waters. The increase in commercial and logistics vessel traffic creates vulnerabilities to transnational crimes such as smuggling, drug trafficking, and illegal fishing, making it essential to strengthen the capacity to monitor and repress illegal activities.

Additionally, the environmental dimension must be considered within the scope of national defense, since ecological disasters can compromise the social and economic stability of the region. Oil spills or accidents involving offshore platforms could severely harm marine ecosystems and coastal communities, requiring swift and effective responses from the Brazilian government. The study by Greenberg *et al.* (2016) analyzed findings from response exercises in oil spill cases. According to the authors, the capabilities needed to respond to emergencies can be organized into three complementary categories. The first corresponds to functional capabilities, of a technical and operational nature, directly associated with the execution of specific tasks during the response, such as spill containment, cleaning of affected areas, and issuing public alerts. The second refers to managerial capabilities, which encompass organizational and interpersonal skills, including leadership, decision-making, coordination, and communication – essential elements for coordinating teams and resources in different types and scales of disasters. Finally, a third category stands out, often neglected in practical guidelines, comprised of adaptive capabilities, which allow one to cope with unforeseen and dynamic scenarios. This set includes skills such as improvisation, flexibility, and the transfer of knowledge acquired from previous experiences, which is fundamental given the inherent uncertainty

that characterizes disaster situations. Thus, it is evident that the integration of contingency plans between the Armed Forces, environmental agencies, and companies in the oil sector must be improved to mitigate potential impacts.

The geopolitics of the Equatorial Margin must also be analyzed considering the interests of foreign powers in the region's strategic resources, as can be seen in the dynamics of countries that are already more advanced than Brazil in the exploration of the region: Guyana and Suriname (Redação, 2025). There is a potential impact on issues related to national defense due to tensions between Venezuela and Guyana, which intensified after the announcement by the US oil company ExxonMobil that the coast of the Essequibo region has great potential for oil and gas exploration (Silva, 2025). The debate between focusing on fossil fuels versus renewable energies in the global scenario may generate external pressures on Brazil regarding its oil exploration and commercialization policy. In this sense, the relationship between the subject presented and the area of defense demonstrates a need for action by the Ministry of Foreign Affairs on the topic, which adds to Nina's (2020) analysis regarding the importance of involvement in negotiations of so-called "energy diplomacy," essential to preserving sovereignty and national interests.

Finally, national defense in the context of the Equatorial Margin must encompass not only territorial and energy protection, but also infrastructure development and improvement, interagency cooperation, and ensuring environmental sustainability. The State's presence must be reinforced through continuous investments in personnel training, equipment modernization, and the expansion of strategic partnerships, ensuring that, should it proceed, oil exploration in the region occurs safely and in line with Brazil's interests.

3 RECOMMENDATIONS

- Strengthening Satellite Surveillance and Monitoring Capabilities

Reason: The integration of advanced satellite and drone surveillance systems will allow for real-time monitoring of maritime and environmental activities in the Equatorial Margin. This enables rapid response to incidents, such as oil spills, and improves surveillance against external threats.

- Creation of an Interinstitutional Task Force for Energy and Environmental Security

Reason: Coordination between the Navy, Army, Air Force, Censipam, Federal Police, Ibama (Brazilian Institute of Environment and Renewable Natural Resources), and the National Petroleum Agency (ANP) will enable an integrated response to security and environmental protection challenges, ensuring that exploration occurs sustainably and under strict oversight.

- Development of Contingency Plans for Environmental Emergencies

Reason: Creating rapid response protocols for oil spills, structural failures on platforms, and natural disasters reduces environmental impacts and protects coastal communities, strengthening the resilience of operations in the Equatorial Margin.

- Development of Cyber Defense Programs focused on the Protection of Offshore Infrastructures

Reason: With the rise in digital threats, protection against cyberattacks on oil platforms and control systems is essential to prevent production disruptions and leaks of sensitive data.

- Enhancing Energy Diplomacy

Reason: Brazil's diplomatic efforts must be strengthened to ensure that exploration of the Equatorial Margin occurs under clear rules, preserving national interests in the face of external pressures and positioning the country as a key player in the governance of energy resources.

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Citizen Selective Collection Program: an analysis of its implementation in the Brazilian Army

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Executive Summary

The Citizen Selective Collection Program is a public policy for solid waste management, which establishes that recyclable waste generated by public administration entities should be primarily destined for associations and cooperatives of recyclable material collectors (Brazil, 2022a). In Brazil, this program has been operating since 2006 as the Solidarity Selective Collection Program, having its name changed with the regulation of the Brazilian National Solid Waste Policy (PNRS) in 2022. The Brazilian Army, as well as other federal public bodies, participates in the program, implementing actions to expand the contribution of its Military Organizations (OM) in the process of proper disposal of solid waste (Brasil, 2006; Brasil, 2022a). The disposal of waste for recycling, through commitment agreements with cooperatives and municipalities, generates environmental and social benefits, fostering the circular economy and valuing waste pickers. However, the weak articulation with local entities and the low capillarity of recycling in the North, Northeast and Central-West regions limit its expansion. This work analyzes the program in the Brazilian Army, focusing on structural advances and limitations. The case study

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covers 67 Military Organizations from 10 Military Regions, between March 2024 and April 2025, with a qualitative approach and document analysis (Cervo; Bervian; Silva, 2007; Gil, 2008). The results achieved highlighted the importance of the program for improving the environmental management of military organizations and emphasized the need to expand partnerships, institutionally strengthen cooperatives and associations, and overcome logistical obstacles that hinder the full implementation of the Citizen Selective Collection within the scope of defense activities.

Keywords: recycling; circular economy; selective collection; sustainability.

1 INTRODUCTION

Solid waste management (SWM) is a growing challenge, driven by population growth, disposable consumption, and inadequate disposal, with environmental and health risks (Gouveia, 2012).

In 2020, the world generated 2.1 billion tons of municipal solid waste (MSW), with 805 million tons improperly disposed of and 404 million tons recycled. By 2050, it is projected to reach 3.8 billion tons, with 1.6 billion tons improperly disposed of, which will exacerbate environmental and health impacts (UNEP, 2024).

In 2023, Brazil generated 81 million tons of MSW (382 kg/inhabitant). Of this, 85.6% went to landfills or dumps, and only 8.3% were recycled (ABREMA, 2024). The data reinforce the urgency of public policies to change behaviors and strengthen management.

Given the territorial extension and socioeconomic diversity of Brazil, municipalities adopt various methodologies for MSW management. These strategies range from contracting private companies to entering into contracts with urban cleaning concessionaires, responsible for the collection, transportation, and final disposal of waste (ABREMA, 2024).

The Brazilian Army, subject to the Brazilian National Solid Waste Policy (PNRS), has approximately 600 military units and 215,000 military personnel throughout the country, generating waste according to national standards. This scenario reveals high potential for sustainable actions aimed at proper waste management.

Municipal solid waste management improves environmental health and contributes to mitigating climate change. Recycling avoids the extraction of natural resources and reduces

greenhouse gas (GHG) emissions by replacing virgin raw materials and decreasing the amount of waste sent to landfills (Borges *et al.*, 2024).

Ongoing climate change impacts the planet globally, with direct repercussions on the security of countries. Caused mainly by human actions linked to GHG emissions, these changes have been recognized as risk factors to the internal and external stability of countries. According to Gomes Filho (2024), this new reality has been incorporated into the strategic and operational planning of the Armed Forces, with repercussions in high-level defense documents in several nations.

In this context, this work analyzes the results of the implementation of the Citizen Selective Collection Program in the Brazilian Army, its advances and structural and operational limitations. The research is classified as applied, as it aims to solve a practical problem, is exploratory in nature, and has a qualitative approach, developed through a case study (Gil, 2008), analyzing the implementation of the Citizen Selective Collection adopted by Military Organizations of 10 Military Regions, between the years 2024 and 2025.

As a technical procedure, documentary research was used, which, according to Cervo, Bervian and Silva (2007), includes the collection, selection, analysis and interpretation of institutional documents as primary data sources, allowing an understanding of the actions in the analyzed context.

2 SELECTIVE COLLECTION BY RECYCLING ASSOCIATIONS AND COOPERATIVES

The disposal of MSW in landfills, besides representing a significant risk to the environment, poses risks to waste pickers, who seek recyclable waste to generate income. Given the need to close landfills and the urgency to promote the social inclusion and economic empowerment of these workers, a Federal Decree was published in 2006 establishing the Solidarity Selective Collection Program, marking the beginning of public policies aimed at encouraging the destination of recyclable waste to waste pickers (Brasil, 2006).

This agenda for progress was strengthened in 2010 with the enactment of the PNRS, which established the mandatory elimination of open dumps and the recognition of waste pickers as fundamental agents in the recycling chain (Brasil, 2010a).

In 2022, the Solidarity Selective Collection Program was renamed the Citizen Selective Collection Program, reinforcing the participatory nature of the initiative and the central role of

waste pickers and civil society, in line with the principles of the circular economy. (Brasil, 2022a). In the same year, the National Solid Waste Plan (PLANARES) was published, which reinforces the principles of selective collection, highlighting the need to expand actions and promote the productive inclusion of waste pickers (Brasil, 2022b).

As highlighted by Cruz, Ferreira, and Garcia (2024), recycling plays a fundamental role in job creation and the promotion of social inclusion, especially in low-income communities that depend on collecting recyclables as a means of subsistence. Despite regulatory advances and implemented incentive mechanisms, Brazil still faces structural challenges in MSW management, which directly impact defense activities throughout the country.

The precarious structural conditions of the North, Northeast, and Central-West regions, where open dumps prevail and cooperatives are absent, highlight flaws in policy implementation and compromise the inclusion of waste pickers (Brasil, 2023).

Regarding the recycling chain, the diagnosis revealed that, of the 1,921 cooperatives and associations of waste pickers reported by the participating municipalities, 36% are located in the Southeast region, 31.5% in the South, 19.8% in the Northeast, 7.7% in the Central-West, and only 4.1% in the North region of the country. These data indicate greater structuring of selective collection in the South and Southeast regions and highlight the need for improvements in the other regions (Brazil, 2023).

Table 1 - Distribution of associations and cooperatives of waste pickers by region of Brazil

Macroregion	Number of cooperatives/associations of waste pickers	Number of members	Average number of members by cooperative/association
North	79	1,783	22.6
Central-West	147	3,247	22.1
Northeast	381	10,088	26.5
South	605	10,802	17.9
Southeast	709	13,079	18.4

Source: Adapted from Brasil, 2023.

Regional inequality in waste disposal and recycling infrastructure highlights shortcomings in the implementation of public policies and points to the need for specific strategies and targeted investments. In this context, the difficulty faced by many municipalities in financing MSW management exclusively through the Public Cleaning Tax stands out.

The PNRS established, as one of the minimum contents of PLANARES, the definition of targets for the elimination and recovery of open dumps, determining that the environmentally sound final disposal of waste should have been implemented by December 31, 2020 (Brasil, 2010a).

However, with the update of the basic sanitation legal framework in 2020, the deadlines were redefined for municipalities that, by that date, had prepared the Integrated Solid Waste Management Plan and had collection mechanisms capable of ensuring the economic and financial sustainability of the services (Brasil, 2020). Currently, a bill is being processed in the National Congress that proposes extending the deadline for municipalities with up to 50,000 inhabitants until August 2, 2029 (Brasil, 2024a).

Despite the significant progress of the regulatory and institutional framework aimed at MSW management in Brazil, with emphasis on the valorization of waste pickers and the creation of economic and reverse logistics instruments, structural challenges still persist that compromise the effectiveness of these policies.

3 SOLID WASTE MANAGEMENT IN THE BRAZILIAN ARMY

3.1 ARMY GUIDELINES FOR SOLID WASTE MANAGEMENT

The Directorate of Real Estate and Environment (DPIMA), under the Department of Engineering and Construction, is the body responsible for standardizing, guiding, and coordinating asset and environmental management actions within the Brazilian Army. Among its responsibilities, the development of guidelines focused on the management of solid waste stands out.

With several military organizations classified as large waste generators, some of them have been excluded from municipal public waste collection services in their localities. In light of this scenario, and with the aim of guiding environmentally sound waste management and optimizing the use of public resources, DPIMA published General Instruction 20-10 (IG 20-10), establishing the guidelines for the Environmental Management System of the Brazilian Army (SIGAEB). This system encourages the implementation of selective collection and the recycling of waste (Brasil, 2008).

Complementing this regulation, Regulatory Instruction 50-20 (IR 50-20) was published, establishing procedures for the correct implementation of SIGAEB. IR 50-20 emphasizes the

mandatory nature of selective collection and the preparation of a Solid Waste Management Plan (PGRS), reinforcing the importance of the correct disposal of recyclable waste (Brasil, 2011).

In line with the evolution of national environmental legislation, the Brazilian Army published, in 2010, regulations establishing guidelines for institutional adaptation to the PNRS. This document defines specific responsibilities for military organizations, such as the inclusion of waste management, selective collection, and recycling actions in Basic Environmental Management Plans (PBGA), in addition to the obligation to prepare PGRS in accordance with the current legislation (Brasil, 2010b).

With the aim of disseminating these practices and facilitating their implementation in the units, the Army's Environmental Handbook (CAmbEx 1) was developed, which guides the preparation and execution of Environmental Management Plans (PGA) and Solid Waste Management Plans (PGRS), in addition to encouraging the formalization of partnerships focused on selective collection, reverse logistics, and recycling of solid waste (Brasil, 2019).

Considering that the implementation of PGRS requires financial planning and adequate allocation of resources, the Guidelines for Administrative Agents assigned to DPIMA the responsibility for decentralizing the resources destined for the execution of services for the collection, treatment, and disposal of common and hazardous waste. Waste from healthcare services and waste from the cleaning of effluent treatment systems are excluded from this responsibility (Brasil, 2024b).

However, there was a significant increase in the number of direct contracts for the collection, transportation, and proper disposal of this waste, which raised operational costs. By 2024, these costs had already reached approximately R$ 12 million, considering services provided in 90 Military Organizations.

To ensure proper contract execution and efficiency in the use of public resources, DPIMA published a Technical Note, which guides the analysis of requests for authorization for new contracts and extensions related to waste management. The document seeks to ensure technical and financial compliance, control budgetary decentralization, promote the circular economy, and reinforce the need to implement Citizen Selective Collection (Brazil, 2024c).

According to Gomes Filho (2024), climate emergencies tend to intensify the competition for public resources, reducing the budgetary space for traditional military investments. In this scenario, sustainable actions such as those conducted by DPIMA demonstrate that sustainability can be an ally of administrative efficiency and strengthen the Brazilian Army's engagement with the contemporary climate agenda.

3.2 IMPLEMENTATION OF THE CITIZEN SELECTIVE COLLECTION IN THE BRAZILIAN ARMY

To raise awareness among military personnel regarding the correct segregation of solid waste, DPIMA implemented environmental education initiatives. Through a review of documents in DPIMA's Internal Bulletins, records of training sessions held at events were identified.

Table 2 - Instructional activities

Event	Date	Instruction
Real State and Environment Meeting (REUPIMA)	27 to 29 February 2024	Citizen Selective Collection
Virtual Seminary - Management of Solid Waste Contracts	4 and 5 June 2024	Methodology for Analyzing Waste Management Contract Authorizations
General Environmental Training for Officers	16 and 25 October 2024	Solid Waste Management

Source: Designed by the authors (2025).

Documentary analysis of the monitoring of the implementation of the Citizen Selective Collection program showed that, in parallel with environmental education actions, the preparation of public calls for proposals was monitored, as well as the signing of commitment agreements with associations and cooperatives of waste pickers. As a result of these initiatives, the participation of 67 Military Organizations was recorded, distributed across 10 Military Regions.

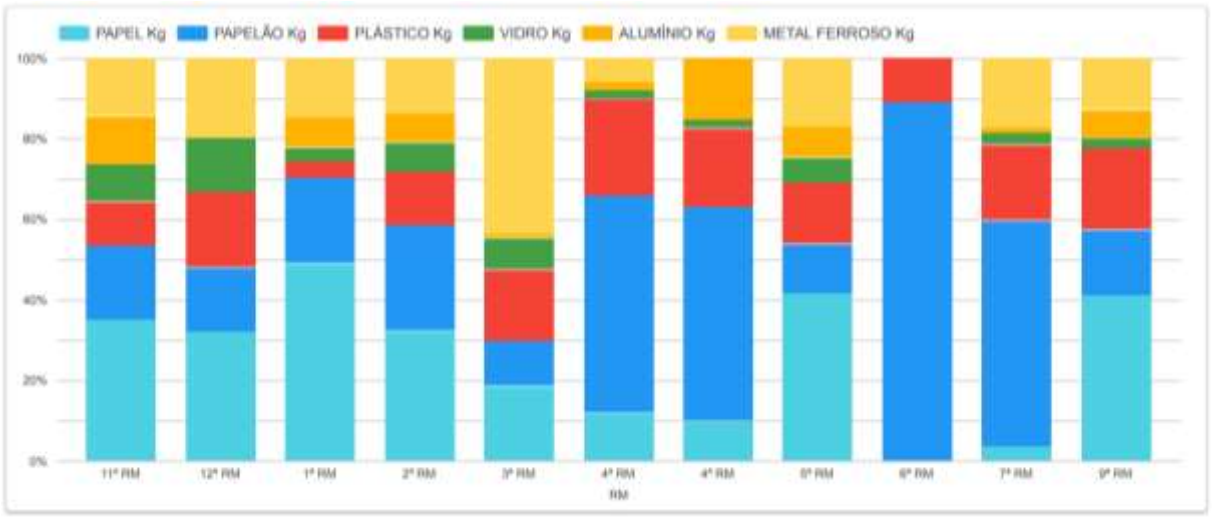
Figure 1 – Citizen Selective Collection: distribution of Military Organizations by Military Region

Source: Designed by the authors (2025).

Analysis of the distribution of the Military Organizations reveals that, in municipalities without structured selective collection or trained cooperatives, the effectiveness of recyclable waste management remains limited. This scenario reflects the national reality, marked by the absence of local solutions and appropriate technologies, as well as logistical and economic difficulties, especially in regions far from sorting or recycling centers.

The data from the monitoring carried out by DPIMA also allowed for the identification of recyclable waste generated by Military Regions, enabling the comparison of waste generation profiles by type in different regions, which is useful for guiding the implementation of the Citizen Selective Collection program.

Figure 2 – Generation of recyclable waste by type



Source: Designed by the authors (2025).

Despite the challenges, the performance of the Military Organizations stands out as an important institutional achievement, as between March 2024 and April 2025, they allocated 485,147.6 kg of recyclable waste to associations and cooperatives of waste pickers. This initiative generated direct savings of over R$ 300,791.51 for public coffers by avoiding additional costs in waste disposal contracts.

It is estimated that implementing the initiative in the approximately 600 active OMs in the country could generate annual savings of approximately R$ 2,693,213.13. This action highlights the potential of Citizen Selective Collection as an effective instrument for environmental management and for promoting the socioeconomic inclusion of members of waste picker cooperatives.

It is noteworthy that these results are consistent with the findings of Trigo *et al.* (2021), who analyzed the implementation of the then Solidarity Selective Collection at the Celso Suckow da Fonseca Federal Center for Technological Education (CEFET/RJ), with regard to cost-effectiveness in public administration.

Nascimento *et al.* (2013), when presenting the methodology used for the implementation of the program at the Research Campus of the Paraense Emílio Goeldi Museum (MPEG), conclude that the implementation of selective collection goes beyond compliance with the guidelines of the Federal Decree, being fundamental to fostering an institutional culture committed to the social inclusion of recyclable material collectors.

Faced with the growing impacts of climate change, the Armed Forces are challenged to adapt their structures and missions. According to Gomes Filho (2024), these impacts manifest

themselves in six main areas: (1) the debate on the role of the Armed Forces as emitters of greenhouse gases; (2) the dispute over public resources, given the demand for investments in mitigation and adaptation; (3) the direct effects on military areas, facilities and equipment; (4) the increased involvement in civil defense missions; (5) involvement in humanitarian operations in areas affected by natural disasters; and (6) the possibility of high-intensity conflicts with environmental motivations.

In this context, DPIMA's actions, through the Citizen Selective Collection program and environmental education, constitute an effective response to these demands. By promoting proper waste management and encouraging reverse logistics practices, it contributes to reducing the environmental footprint of the Military Organizations. Furthermore, the direct savings of over R$ 300,000, with the potential to increase to R$ 2 million, demonstrates the compatibility between sustainability and budgetary efficiency. Finally, by integrating sustainability into military training and doctrine, it reinforces the Brazilian Army's commitment to environmental preservation.

4 RECOMMENDATIONS

- Expand the debate on Citizen Selective Collection among public institutions, fostering networking and direct interaction with waste pickers, encouraging the formation of associations and cooperatives, especially in the North region.

- Implement actions aimed at the environmentally sound disposal of solid waste, reducing the total volume generated, and optimizing the transport of recyclable waste to units closer to waste picker associations and cooperatives, as well as including composting methodology for organic waste, especially in more isolated Military Organizations, such as the Special Border Platoons.

- Improve the ongoing training of military and civilian personnel of the Brazilian Army, focusing on solid waste management practices, reverse logistics, and the implementation of Citizen Selective Collection, in partnership with public institutions present in the most deficient regions.

- Promote the signing of agreements between the Brazilian Army and local environmental agencies for the integration of Military Organizations into local waste management systems, enabling the sharing of infrastructure for sorting, storing, and transporting recyclable waste.

- Incorporate the climate variable into the environmental planning of Military Organizations, promoting the adoption of strategies to mitigate and adapt to the impacts of climate change, with an emphasis on nature-based solutions, energy efficiency, and resource conservation.

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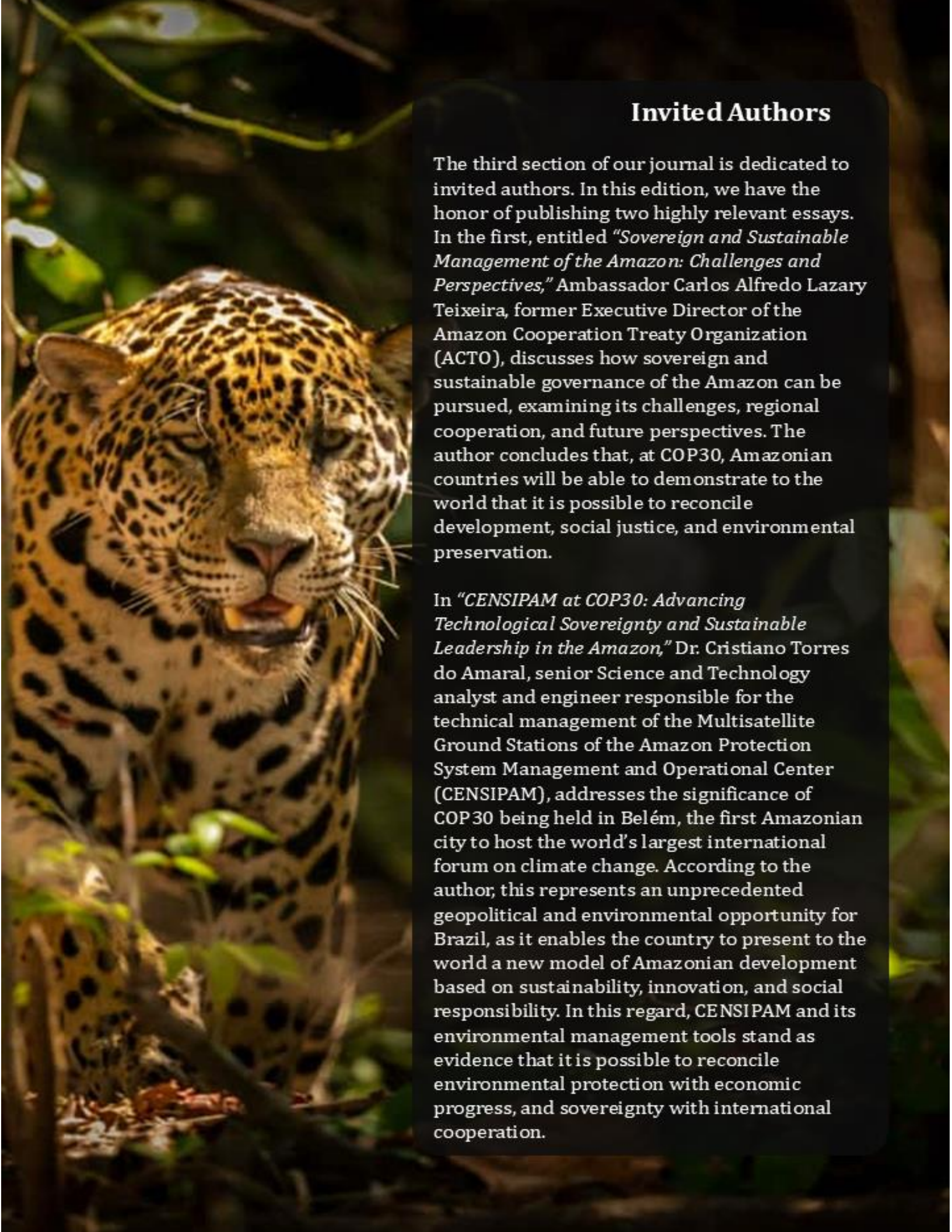

Invited Authors

The third section of our journal is dedicated to invited authors. In this edition, we have the honor of publishing two highly relevant essays. In the first, entitled *"Sovereign and Sustainable Management of the Amazon: Challenges and Perspectives,"* Ambassador Carlos Alfredo Lazary Teixeira, former Executive Director of the Amazon Cooperation Treaty Organization (ACTO), discusses how sovereign and sustainable governance of the Amazon can be pursued, examining its challenges, regional cooperation, and future perspectives. The author concludes that, at COP30, Amazonian countries will be able to demonstrate to the world that it is possible to reconcile development, social justice, and environmental preservation.

In *"CENSIPAM at COP30: Advancing Technological Sovereignty and Sustainable Leadership in the Amazon,"* Dr. Cristiano Torres do Amaral, senior Science and Technology analyst and engineer responsible for the technical management of the Multisatellite Ground Stations of the Amazon Protection System Management and Operational Center (CENSIPAM), addresses the significance of COP30 being held in Belém, the first Amazonian city to host the world's largest international forum on climate change. According to the author, this represents an unprecedented geopolitical and environmental opportunity for Brazil, as it enables the country to present to the world a new model of Amazonian development based on sustainability, innovation, and social responsibility. In this regard, CENSIPAM and its environmental management tools stand as evidence that it is possible to reconcile environmental protection with economic progress, and sovereignty with international cooperation.

Sovereign and sustainable management of the Amazon: challenges and perspectives

Carlos Alfredo Lazary Teixeira[*]

Introduction

The Amazon is one of the most emblematic regions on the planet. Located in nine South American countries, of which Brazil concentrates the largest part, it is home to the largest continuous tropical forest in the world, responsible for enormous biological diversity and climatic processes that transcend national borders. Therefore, it is considered a natural heritage of global importance.

However, the Amazon is not just an environmental issue. It also represents a strategic space for the sovereignty of the countries that comprise it, a reservoir of mineral, water and genetic wealth, as well as being home to millions of people, including indigenous peoples and traditional communities. The management of the region, therefore, requires reconciling multiple dimensions: preserving its biodiversity, guaranteeing quality of life for the population, promoting sustainable economic development and, at the same time, asserting national sovereignty.

This article discusses how it is possible to conduct sovereign and sustainable management of the Amazon, exploring its challenges, regional cooperation, and prospects for the future.

The Amazon as a strategic asset

The Amazon basin covers approximately 7 million km², of which about 5 million are in Brazilian territory. This vast area holds about 20% of the planet's surface freshwater and plays a crucial role in global climate regulation through the hydrological cycle that influences rainfall in various parts of South America.

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The Amazon's heritage goes beyond biodiversity: it contains strategic mineral reserves, energy potential, large timber stocks, and a vast genetic heritage that can serve as a basis for biotechnology and medicine. This wealth makes the region a target of international interest.

Recurring narratives that advocate for the "internationalization of the Amazon" or treat it as a common good of humanity often disregard the sovereignty of the countries located within it. While it is undeniable that the preservation of the forest has a global impact, the responsibility for deciding on its territory, its exploitation, and its conservation rests primarily with the Amazonian states. This tension between the national/regional dimension and the global dimension of the Amazon is one of the central points of sovereign governance.

In this sense, it is important to recall the signing of the Amazon Cooperation Treaty (ACT) in 1978, initiated by Brazil, motivated primarily by the imperative need to assert the sovereignty of the eight countries over the area, countering repeated accusations of unsuitability to handle the challenge of promoting its "responsible" management. To this end, the Brazilian government relied on the strength of its defense of the link between development and the environment during the UN Conference held in Stockholm in 1972. It also relied on the successful negotiation and signing, shortly before, in 1969, of the Treaty of the River Plate Basin. With the ACT, therefore, formal diplomatic coverage was given to the two main hydrographic basins of South America.

Nationally, it is useful to recall the creation of the Calha Norte Program, established in 1985 within the context of Brazil's redemocratization. Originally conceived as a national defense initiative focused on military presence along the Amazonian border, the program sought to ensure territorial integrity in the face of external pressures such as, for example, the threats of foreign intervention in Suriname following the coup carried out by Sergeant Dési Bouterse in 1980. The Amazon region, sparsely populated and with low population density, was perceived as vulnerable to foreign interests. Therefore, the logic of Calha Norte was centered on security and territorial control. This same logic motivated, in relation to airspace control, the implementation of the Amazon Surveillance System – SIVAM.

Over time, however, Calha Norte and SIVAM incorporated civil and social dimensions. Renamed the Management and Operational Center of the Amazon Protection System (CENSIPAM), the program began to finance basic infrastructure, health, education, and sustainable development projects in municipalities in the Northern region. Thus, it became an

instrument not only of national defense, but also of State presence and support for regional development, reaffirming sovereignty through public policies.

This movement towards the northern part of Brazil cannot be fully understood without considering the holistic effect of the change of the federal capital to Brasília, also including the geopolitical and diplomatic dimension. The ACT is part of this construction.

Challenges of Amazonian sustainability

The Amazon rainforest faces constant pressures that compromise its sustainability. Deforestation is the most visible of these. The opening of new areas for agriculture and livestock farming, coupled with land grabbing and illegal burning, causes biodiversity loss and threatens the collapse of the region's ecosystem services. It is estimated that if deforestation exceeds a certain threshold, the forest could enter a process of *savannization*, losing its ability to maintain rainfall cycles and store carbon.

Another critical challenge is mining. While legal mining can be regulated and monitored, illegal mining is growing unchecked, especially on indigenous lands and in environmental protection areas. This activity causes mercury pollution, river degradation, and violence against local communities.

Climate change is exacerbating existing problems. Rising average temperatures and reduced humidity in some areas have already led to prolonged droughts and more intense wildfires. This compromises both biodiversity and regional agriculture, as well as increasing the risk of extreme events on a continental scale.

From a social perspective, Amazonian sustainability also involves the protection of indigenous peoples and traditional communities. They are guardians of vast territories and possess ancestral knowledge about the forest. However, they suffer from invasions, violence, discrimination, and lack of access to basic services. The inclusion of these populations in management processes is essential for any sustainability project.

Management models and public policies

Managing the Amazon requires integrated policies that combine environmental protection, economic development, and social inclusion. Among the existing instruments, the Ecological-Economic Zoning stands out, guiding land use according to its environmental and social

characteristics. Although it is a fundamental tool, recognized as such by the region's governments, its implementation throughout the biome is still partial and uneven.

Strengthening environmental enforcement is also essential. In Brazil, agencies such as IBAMA (Brazilian Institute of Environment and Renewable Natural Resources) and ICMBio (Chico Mendes Institute for Biodiversity Conservation) play a crucial role in combating environmental crimes and, therefore, have been strengthened to overcome the ever-present budgetary difficulties, political pressures, and, at times, personnel limitations. They are indispensable actors in Brazil's leadership in implementing the ACT, through the tool of South-South cooperation, alongside centers of excellence and best practices such as FIOCRUZ (Oswaldo Cruz Foundation) and INPE (National Institute for Space Research) , among others, always with the effective and recognized support of the Brazilian Cooperation Agency. Public policies for the Amazon, as prescribed by the ACT, must be strengthened to the point of becoming permanent and convergent state policies, aimed at reducing the double asymmetry that characterizes the region: between the co-owner countries, in terms of presence and institutional capacity, and in each country, in relation to the rest of the national territory. Hence the importance of South-South cooperation; without discarding the scientific and financial contribution of actors from outside the region.

On the other hand, and in addition, the effectiveness of public policies depends on monitoring capacity. Here, the role of excellent Brazilian entities such as INPE, with its expertise in capturing and analyzing satellite images of forest cover and water bodies, becomes apparent again. In this context of South-South monitoring and cooperation, it is worth mentioning Brazil's establishment of the Amazon Fund, with the support and significant financial contributions from Norway and Germany, which reserved up to 20% of its resources for monitoring projects across the entire biome and basin, including activities in neighboring countries.

Another central aspect of the ACT is the comprehensive and integrated management of water resources. The Amazon Basin is home to internationally important rivers and enormous potential for groundwater, such as the *Alter do Chão* aquifer in Brazil. A project is underway to map these resources in the subsoil of Bolivia, Brazil, Colombia, Ecuador, Peru, and Venezuela, funded by the Global Environmental Facility (GEF), which will certainly confirm the existence of extensive reservoirs. However, the abundance of freshwater does not eliminate the risks of local scarcity, decreased water quality, or conflicts over its use. Energy production, navigation, urban water

supply, fishing, agricultural irrigation, and ecosystem maintenance depend on coordinated policies among all countries. Integrated water resource management implies considering cumulative impacts, promoting social participation, reconciling different uses, and fostering cooperation among Amazonian countries. This systemic vision reinforces that water must be treated as a strategic element of sovereignty and as a factor in regional integration.

From a development perspective, the concept of bioeconomy is gaining strength, seeking to generate wealth from products of the standing forest. Production chains based on açaí, Brazil nuts, vegetable oils, sustainably managed timber, and biotechnology are examples of alternatives that combine preservation and income generation. To prosper, however, the bioeconomy requires infrastructure, scientific research, innovation, and access to markets. Closely related to the bioeconomy, perhaps even fitting into the broader concept, is sustainable community-based tourism, due to the beneficial effects described above and also its capacity to reduce the exodus of new generations to large urban centers.

Regional integration and international cooperation

The Amazon transcends national borders. The biome extends across eight countries besides Brazil: Bolivia, Colombia, Ecuador, Guyana, Peru, Suriname, Venezuela, and the Department of French Guiana. This diversity makes regional cooperation indispensable for managing the forest, with a view to advancing integration.

In this context, the Amazon Cooperation Treaty Organization (ACTO) is the main institutional mechanism. Created in 1998, when the ACT turned 20, and established in 2002, it brings together the Amazonian countries to promote cooperation in areas such as water resources, science, technology, health, education, indigenous peoples, cross-border illegal activities, and biodiversity protection. Although it has faced limitations in resources and political protagonism, ACTO has strengthened remarkably in the last six years, becoming an indispensable actor in promoting the sustainable development of the Amazon in its three dimensions: the basin, the biome, and the region, understood as the geographical space resulting from the sum of the territories declared by the countries as covered by the ACT.

The organization operates through technical cooperation projects, primarily funded by international agencies, banks, and funds, such as the German GIZ, IDB, UNEP, and GEF (through implementing agencies). Projects are developed with the unanimous agreement and participation

of the governments of member countries, without external constraints. Its agenda is positive: it mainly aims to build the capacity of the institutions responsible in each country for public policy to be benefited. This is the case with the hydrometeorological monitoring network of the basin, with hundreds of physical stations spread along the banks of international rivers, as well as the capacity building of countries to enable the implementation of the CITES Convention (Convention on International Trade in Endangered Species of Wild Fauna and Flora) on the protection of endangered species of fauna and flora within their territories.

The strengthening of the ACTO is directly proportional to the affirmation of the sovereignty of its members in the region, insofar as it represents a platform for articulating common positions before the international community, in the forums for negotiating the sustainable development agenda, aiming at the protection of biodiversity and the promotion of the well-being of the Amazonian people. Knowledge management, through the Amazon Regional Observatory, is an essential part of this strengthening, provided that its construction and operation result in an effective contribution to public policies and real appropriation by the inhabitants of the Amazon. The recently created Scientific Panel within the ACTO and UNAMAZ (the Association of Amazonian Universities), which is undergoing an accelerated process of revitalization, will contribute substantially to this.

A recent example of ACTO's actions occurred in the dispute over the top-level domain “amazon” (dot or dot amazon) with ICANN (Internet Corporation for Assigned Names and Numbers). Amazon Inc. sought exclusive use of the domain, which would give it the right to use it globally as its corporate digital identity. The Amazonian countries, coordinated by ACTO, argued that the term “Amazon” refers not only to a company, but above all to a geographical and cultural region, essential to millions of people and to the planet's environmental balance.

Despite the pressure, ICANN's decision ultimately favored the corporation, which obtained the domain name concession, but indicated the need to establish a steering committee for the domain, which has not yet occurred due to resistance from Amazonian countries to the company's imposition of total control over the committee. The actions of ACTO, led by then Secretary-General Alexandra Moreira (2019-2024), represented an important affirmation: the defense of the digital sovereignty of the Amazonian states and the region's identity against private appropriation. This episode shows that Amazonian sovereignty also needs to be considered in new dimensions, such as the virtual sphere.

In August 2023, Brazil hosted the IV Summit of Presidents of the States Parties to the ACT, known as the Amazon Summit, in Belém, Pará. On that occasion, the Belém Declaration was approved, containing over one hundred operational paragraphs, resuming and expanding upon the agenda of Amazonian cooperation built over the 45 years since the signing of the Treaty. Two messages stood out: the need to incorporate civil society into the process of building the cooperation agenda and the commitment, linked to knowledge management, to base public policies for the Amazon on the best existing and available scientific information, always valuing the ancestral knowledge of the Amazonian peoples.

There was also consensus that mobilization should continue at the presidential level, due to the evident political effect on the international community of calmly and consciously asserting sovereignty over the Amazon. Thus, at the V Summit, held in Bogotá, Colombia, in August 2025, the leaders decided to move forward with the formal inclusion of presidential meetings as a superior instance in the governance of the ACT.

The ACT gained additional importance as a result of the unwelcome disbanding of UNASUR (Union of South American Nations), whose agenda was left adrift, not only in the field of diplomacy and integration, but particularly in relation to defense and public security/cross-border crimes, both with clear links to the Amazon. In the diplomatic sphere, the ACT became the remaining institutional and political link between Suriname and Guyana and their South American context. Regarding defense, the issues of the South American Defense Council have not yet found a foothold, despite the timid efforts of the Brazilian government. Regarding illegal activities, Brazil took an important step in September 2025 with the inauguration in Manaus of the CCCPI Amazônia (Amazon International Police Cooperation Center), a groundbreaking platform for cooperation with our Amazonian neighbors, for training and exchange in intelligence and joint actions to combat transnational crimes in the region (deforestation, illegal mining, illegal trade in endangered species of fauna and flora, drug trafficking, arms trafficking, and human trafficking), with investments of approximately R$ 36.7 million from the Amazon Fund. In his speech at the CCPI inauguration ceremony, President Lula da Silva made an explicit connection to the theme of sovereignty: "…we do not need foreign interventions, nor threats to our sovereignty. We are perfectly capable of being protagonists in our own solutions."[1]

[1] Free translation by the translator.

Future perspectives

The future of the Amazon will depend on the ability of its countries to promote a new development model. The unlimited expansion of the agricultural frontier and mineral exploitation is not sustainable. On the contrary, it threatens to irreversibly compromise the forest and the environmental services on which Brazil, South America, and the world depend.

Among the alternatives are strengthening the bioeconomy, valuing the traditional knowledge of indigenous peoples and local communities, investing in science and technology for biotechnology and medicine, as well as the sustainable management of forest resources. These strategies can generate employment, income, and innovation, while preserving the forest.

It is equally necessary to expand the State's presence in the region. This means not only strengthening environmental oversight, but also guaranteeing infrastructure, health, education, and security for local inhabitants. Sovereignty is affirmed by the State's ability to offer dignified living conditions to its population and exercise effective authority over the territory.´

Regional and international cooperation will continue to be an important pillar. However, it must be conducted on a basis that respects national sovereignty and strengthens the internal capacities of the Amazonian countries.

In this context, the holding of COP 30 in Belém, Pará, in 2025, is particularly noteworthy. For the first time, a Conference of the Parties to the United Nations Framework Convention on Climate Change will be hosted in the Amazon. The event represents not only recognition of the region's centrality to global climate balance, but also a strategic opportunity for Brazil and its Amazonian neighbors to present concrete commitments regarding deforestation, energy transition, and biodiversity preservation. The conference will constitute a strategic opportunity for Brazil and other Amazonian countries to demonstrate their commitment to the sustainable development of the region and, specifically, to jointly address the challenges of climate change and global warming. Furthermore, the event will allow Amazonian countries to reaffirm not only their commitment to sustainable development, but also their sovereignty over the region, showing the world that the preservation of the Amazon must be guided by the decisions and priorities of the Amazonian states themselves.

Conclusion

The Amazon is simultaneously a national and global challenge. Its preservation is in the interest of humanity, but its management belongs, first and foremost, to the countries that comprise it. The balance between sovereignty and sustainability is key to guaranteeing the future of the forest.

Sovereign and sustainable management must articulate environmental protection, inclusive economic development, empowerment of local communities, and balanced international cooperation. Brazil, as the country that holds the largest portion of the forest, has a central role in this process, but the effort needs to be collective, involving all Amazonian countries and society as a whole.

Furthermore, Amazonian sovereignty is not limited to physical territory. It includes the protection of its water resources, the defense of its symbolic identity in digital spaces—such as the ".amazon" domain—and the strategic presence of the State through national and regional programs and projects, such as the Calha Norte program and the ACTO agenda. These elements broaden the understanding of sovereignty, showing that it must be comprehensive, encompassing environmental, social, technological, and cultural dimensions.

The holding of COP 30 in Belém reinforces this understanding: the Amazon is the center of global attention and, at the same time, a space for asserting regional sovereignty. This is a historic moment in which the Amazonian countries can show the world that it is possible to combine development, social justice, and environmental preservation. If well managed, the sovereign and sustainable management of the Amazon can transform the region into a global example of how to protect nature without sacrificing the autonomy and prosperity of the peoples who depend on it.

Censipam at COP30: advancing technological sovereignty and sustainable leadership in the Amazon

*Cristiano Torres do Amaral**

The 30th United Nations Conference on Climate Change (Conference of the Parties) represents a turning point in global climate negotiations, especially because it takes place in Belém, Pará, in the heart of the largest and most important ecosystem of the Amazon. For the first time, a city located in the Amazon region will host the largest international forum on climate change, bringing together leaders, scientists, civil society representatives, and the private sector. The symbolism of this choice is immense: the Amazon, considered the largest tropical biome on the planet, takes center stage at a critical moment for the environmental future of humanity. With unique biodiversity and a central role in regulating the global climate, the Amazon rainforest also faces constant threats from deforestation, wildfires, illegal exploitation of natural resources, and environmental degradation. Amid these challenges, Brazil assumes an unprecedented geopolitical and environmental responsibility (UNFCCC, 2025).

The holding of COP30 on Amazonian soil emphasizes the need for assertive responses to the environmental issues affecting the forest. Deforestation, driven by activities such as agricultural expansion and illegal logging, remains one of the greatest threats to the integrity of the biome. In addition, forest fires, often deliberately caused, further worsen the situation, contributing to the release of large amounts of greenhouse gases and the destruction of essential habitats. International pressure for Brazil to act more strictly in combating these environmental crimes is increasing. At the same time, the country faces the challenge of promoting the economic development of the Amazon region, marked by deep social inequalities and lack of infrastructure, without compromising its biodiversity (IMAZON, 2023).

In this context, it becomes essential to present to the world concrete initiatives that articulate environmental preservation, sustainable development, and national sovereignty. The

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Management and Operational Center of the Amazon Protection System (CENSIPAM) emerges as a strategic actor in the environmental scenario. Linked to the Ministry of Defense, CENSIPAM's mission is to integrate information and technologies aimed at the protection and monitoring of the Legal Amazon. Among its technological products are SIPAM Hidro, the Fire Panel, Amazon SAR, and the pioneering mapping of the Amazon with remotely piloted aircraft. All these products offer effective and innovative tools, on different scales, to face the environmental challenges of the region, allowing the Brazilian State to exercise sovereign control over its territory, while promoting sustainable and responsible actions (CENSIPAM, 2025).

The use of drones for mapping the Amazon is an innovation incorporated by CENSIPAM in recent research for monitoring and preserving the ecosystem. Small unmanned aircraft equipped with high-resolution cameras are used to record detailed images of critical areas, such as border regions, conservation units, and indigenous territories. This technology has proven extremely useful for field operations, inspection actions, and data collection in hard-to-access locations. Drone mapping enables more accurate and agile surveillance, favoring the integrated action of different institutions and the engagement of local communities in environmental protection. During COP30, the demonstration of these technological capabilities can reinforce the importance of informational sovereignty over the forest and highlight Brazil's leadership in managing the Amazonian territory (Custódio; Abeledo, 2023).

Another important product is SIPAM Hidro. It is a climate monitoring platform in the Amazon, developed by CENSIPAM. This system represents a strategic advancement for environmental surveillance and facing climate crises. Riverside and urban populations can monitor flood areas during the rainy season as well as river levels during periods of water scarcity. This digital platform plays a central role in the collection, analysis, and dissemination of real-time meteorological data in one of the most sensitive and essential regions for global climate balance: the Amazon rainforest (Nogueira, 2023).

Associated with SIPAM Hidro is also the Fire Panel, which monitors in 'near real-time' the phenomena associated with forest fires in the tropical forest. In digital environments, the platforms developed by CENSIPAM assume strategic importance, as they allow more accurate climate monitoring of the Amazon, feeding databases that assist both in the planning of public policies and in emergency environmental protection and civil defense actions in the Amazon.

CENSIPAM's digital platforms, available in the Panorama system, integrate different sensors distributed in remote points of the forest, meteorological radars, satellite images, and climate modeling algorithms. This robust infrastructure allows the identification of temperature, humidity, precipitation, and wind patterns, generating forecasts that contribute to the prevention of natural disasters and the management of water and agricultural resources. In addition, these data are shared with international centers, such as the United States National Oceanic and Atmospheric Administration (NOAA), promoting essential scientific collaboration for global climate understanding (Amaral, 2025).

CENSIPAM's climatological monitoring platforms not only represent a technological advancement but also a geopolitical and environmental instrument essential for authorities attending COP30, reinforcing Brazil's role as a protagonist in the fight against climate change and in the protection of the Amazon. CENSIPAM's platforms promote a digital transformation of geoinformation, as they provide valuable climatic and environmental data for technical reports, scientific panels, and international negotiations, strengthening Brazil's position as a global environmental leader. In addition, they can support more ambitious commitments to reduce emissions and preserve biodiversity at COP30.

On another scale, the Amazon SAR product uses synthetic aperture radar (SAR) technology for forest monitoring and represents a significant milestone in the environmental protection of the Amazon. This product presents a differentiated methodology that allows the detection of deforestation even under adverse conditions, such as cloud cover, common in the region. This capability is crucial for continuous and effective inspection of tropical forest areas. Implemented with resources from the Amazon Fund, the project aims to complement existing systems, such as DETER, which depend on optical sensors and are limited by the presence of clouds. The SAR Project methodology analyzes high-resolution images during the day or night, regardless of weather conditions, enabling the generation of more accurate and near real-time deforestation alerts (Fundo Amazônia, 2025).

In the Amazon SAR satellite monitoring infrastructure, CENSIPAM's ground stations stand out, installed in strategic locations: Formosa (GO) and Manaus (AM). Currently, CENSIPAM's ground stations receive real-time images from NASA/NOAA Earth observation satellites: Suomi-NPP, JPSS-1, JPSS-2, Aqua, and Terra. The constellation of satellites from the Brazilian Air Force's Project *Lessônia*, and the Amazon I, CBERS 4, CBERS 4A, SCD-1, and SCD-2 satellites, operated by INPE, are also in operation at CENSIPAM's ground stations, providing relevant services to the security and defense of the Amazon.

Finally, the greatest and most important resource of CENSIPAM is its technical staff, which deserves special recognition for their high level of qualification and commitment in monitoring the Amazon. The team consists of engineers, geographers, biologists, remote sensing analysts, and other professionals from the Science and Technology careers. It is a high-level team, a multidisciplinary group that is fundamental to the success of strategic projects such as Amazon SAR. The integrated, inter-agency performance allows for precise analysis of geospatial data, the generation of reliable deforestation alerts, and the production of essential information for governmental decision-making. The technical competence of these professionals reflects the potential of science applied to environmental protection, reaffirming CENSIPAM's role as an institution of excellence in Amazon management.

The hosting of COP30 offers a unique opportunity for Brazil to present to the world a new model of Amazonian development, based on sustainability, innovation, and social responsibility. The integration of CENSIPAM's tools and its contribution to the event's agenda demonstrate that it is possible to reconcile environmental protection with economic progress, and sovereignty with international cooperation. Brazil stands out by showing how technological intelligence applied to environmental management strengthens public policies, increases resilience to climate change, and expands opportunities for sustainable investment. Furthermore, CENSIPAM's active presence during the conference creates new opportunities, partnerships, scientific exchange, and, most importantly, consolidates the country as a global reference in tropical forest monitoring.

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