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ENVIRONMENTAL GOVERNANCE OF AMAZONIAN HIGHWAYS

GESTÃO AMBIENTAL DAS ESTRADAS DA AMAZÓNIA

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Abstract
Amazonian highways generate effects that extend beyond the physical footprint of road infrastructure, influencing ecological integrity, territorial dynamics, and institutional capacity to govern cumulative change. This article examines the environmental governance condition of the Manoel Urbano–Feijó segment of BR-364, in Acre, Brazil, through the application of ISRAM, a multidimensional corridor-scale diagnostic framework. The method integrates five analytical dimensions—Environmental, Technological, Economic, Social, and Institutional—standardized on a 0–1,000 scale to assess how fragility is distributed across interdependent components of corridor performance. Results indicate low overall performance (260.5/1,000), with concentrated weakness in the Environmental and Technological dimensions, revealing a persistent socioecological mismatch between infrastructural functioning, ecological connectivity, and governance capacity. In light of Brazilian Environmental Law, the article argues that environmental licensing remains indispensable, but its legal adequacy in corridor settings depends on territorially coherent area-of-

Resumo
Rodovias amazônicas produzem efeitos que ultrapassam a faixa física da infraestrutura viária, influenciando a integridade ecológica, a dinâmica territorial e a capacidade institucional de governar mudanças cumulativas. O presente artigo examina a condição de governança ambiental do trecho Manoel Urbano–Feijó da BR-364, no Estado do Acre, mediante a aplicação do ISRAM, estrutura diagnóstica multidimensional concebida para análise de corredores em escala territorial. O método integra cinco dimensões analíticas — ambiental, tecnológica, econômica, social e institucional — padronizadas em escala de 0 a 1.000, a fim de avaliar como a fragilidade se distribui entre componentes interdependentes do desempenho do corredor. Os resultados indicam baixo desempenho global (260,5/1.000), com fragilidade concentrada nas dimensões ambiental e tecnológica, revelando descompasso socioecológico persistente entre funcionamento infraestrutural, conectividade ecológica e capacidade de governança. À luz do Direito Ambiental brasileiro, sustenta-se que o licenciamento ambiental permanece

influence definition, cumulative-effects appraisal, federative coordination, and adaptive monitoring beyond the immediate project footprint. Rather than replacing licensing or impact assessment, ISRAM is proposed as a complementary territorial diagnostic for interpreting corridor conditions under cumulative and cross-scalar pressures.

Keywords: Amazon. Environmental Governance. Environmental Licensing. Road Infrastructure. Territorial Planning.

indispensável, mas sua suficiência jurídica, em contextos de corredor, depende da delimitação territorialmente coerente da área de influência, da consideração de efeitos cumulativos, da coordenação federativa e do monitoramento adaptativo para além da pegada imediata do projeto.

Palavras-chave: *Amazônia. Governança Ambiental. Infraestrutura Rodoviária. Licenciamento Ambiental. Planejamento Territorial.*

1 INTRODUCTION

Infrastructure expansion in the Amazon can no longer be understood merely as a technical response to mobility deficits or regional integration demands. In tropical forest regions, highways reorganize access, reshape land values, induce land-use conversion, alter ecological connectivity, and intensify governance pressures far beyond the right-of-way. This is particularly consequential in the Amazon, where forests are increasingly exposed to interacting stresses associated with deforestation, degradation, drought, fire, warming, and hydroclimatic instability (Boulton et al., 2022; Flores et al., 2024; Gatti et al., 2021; Butt et al., 2023). In this setting, highways should not be treated as neutral linear artifacts, but as territorial drivers embedded in coupled ecological, economic, social, and institutional dynamics.

This broader interpretation is supported by recent evidence on infrastructure and land-use change in the Amazon. Araujo, Assunção, and Bragança (2025) show that transportation improvements may substantially underestimate deforestation impacts when effects beyond the immediate project surroundings are disregarded. Vilela et al. (2020) had already demonstrated that several planned road projects in the Amazon generate high environmental and social costs while often failing to maximize development gains. At the same time, the degradation process cannot be reduced to deforestation alone. Matricardi et al. (2020) found that long-term forest degradation in the Brazilian Amazon surpassed deforestation in territorial extent over the period studied; Silva Junior *et al*. (2020) showed that forest-edge effects generated major unaccounted carbon losses; and Lapola *et al*. (2023) synthesized evidence that degradation by fire, edge effects, timber extraction, and extreme drought now affects a vast share of the remaining forest. The central issue, therefore, is not simply whether a road removes forest directly, but whether it embeds the corridor in a cumulative pattern of socioecological fragility.

From a legal and institutional standpoint, this diagnosis reveals an important limitation in conventional infrastructure governance. Environmental assessment remains indispensable, yet project-based procedures are often more capable of identifying bounded impacts than of diagnosing diffuse, cumulative, and territorially coupled transformations. Recent literature on the mitigation hierarchy and biodiversity-inclusive impact assessment continues to identify recurring shortcomings in the treatment of avoidance, cumulative effects, ecological networks, and residual losses (Morrison-Saunders & Sánchez, 2024; Dvořáková *et al*., 2024; Ghijselinck *et al*., 2026). Likewise, road-ecology research indicates that roads reduce landscape permeability, intensify fragmentation, and disrupt wildlife corridors across multiple scales, including in tropical rainforest contexts (Bennett, 2017; Xiong *et al*., 2025). Under such conditions, a corridor may satisfy formal procedural requirements and still remain territorially misread.

Brazilian Environmental Law already offers a relevant normative architecture for confronting these problems, although its practical operation still reveals important limits when the object to be governed is not an isolated project, but an ecologically sensitive corridor. The National Environmental Policy Act recognizes environmental licensing and the review of effectively or potentially polluting activities as core instruments of environmental policy (Brazil, 1981). CONAMA Resolution No. 1/1986 establishes the basic criteria and general guidelines for environmental impact assessment, including highways among the activities typically subject to EIA/RIMA, and requires the analysis of alternatives, area of influence, cumulative effects, and monitoring (CONAMA, 1986). CONAMA Resolution No. 237/1997 further structures environmental licensing as an administrative procedure (CONAMA, 1997). In Brazilian doctrine, such instruments are not mere bureaucratic authorizations, but preventive and integrative mechanisms for controlling environmental risk and disciplining development choices (Machado, 2024; Leite & Bello Filho, 2004).

Even so, the existence of a robust legal framework does not automatically resolve the problem of corridor-scale governance. The challenge lies less in normative absence than in the difficulty of translating legal-environmental commands into integrated territorial intelligence capable of capturing indirect, cumulative, and cross-scalar effects. This difficulty becomes especially relevant in the Amazon, where road interventions interact with frontier expansion, forest degradation, fire dynamics, hydrological disturbance, and institutional asymmetries. Supplementary Law No. 140/2011 distributed administrative competences among the Union, States, Federal District, and Municipalities and preserved a cooperative federalism approach in environmental management (Brazil, 2011). Yet coordination problems remain substantial where environmental liabilities exceed administrative boundaries, involve multiple agencies, or unfold gradually through territorial feedbacks. As environmental law scholarship has long emphasized, governance quality cannot be reduced to formal compliance alone, but must also be assessed in light of its ability to manage complexity, uncertainty, interdependence, and cumulative harm (Sands *et al*., 2018).

For Amazonian highways, this gap is decisive. If corridor impacts are cumulative, territorially mediated, and institutionally distributed, then the relevant unit of analysis cannot remain restricted to the isolated licensed footprint. What must be governed is the corridor as a socioecological-territorial system. This requires moving beyond a narrow paradigm of impact containment toward arrangements capable of integrating ecological connectivity, hydroecological compatibility, territorial planning, and adaptive institutional coordination.

Against this background, the article proposes the Amazon Road Sustainability Index (ISRAM) as a multidimensional framework for diagnosing the environmental-governance condition of Amazonian highway corridors. The empirical application focuses on the Manoel Urbano–Feijó segment of BR-364, in the state of Acre, a corridor that combines logistical relevance with chronic technical deficiencies, environmental vulnerability, and frontier pressures typical of broader Amazonian road dynamics. The article asks to what extent a multidimensional diagnostic framework can better capture cumulative legal-regulatory and socioecological liabilities than mitigation-centered or generic sustainability approaches. In response, it applies ISRAM through twenty-five indicators distributed across five dimensions—environmental, technological, economic, social, and institutional—and argues that the resulting pattern of fragility reveals not only low performance, but a specific governance mismatch between infrastructural functionality, socioecological integrity, and institutional capacity at corridor scale.

The article makes a twofold contribution. Methodologically, it offers a transparent and auditable framework for diagnosing how fragility is distributed across interdependent dimensions of corridor performance. From a legal-institutional perspective, it argues that conventional instruments such as environmental licensing remain indispensable, but require complementary territorial readings capable of identifying cumulative effects, coordination deficits, and adaptive monitoring needs that may remain only partially visible under project-bounded assessment. By doing so, the article contributes to the debate at the intersection of environmental law, infrastructure regulation, and territorial planning, while advancing a more demanding understanding of environmental governance for Amazonian highways.

2 THEORETICAL FRAMEWORK

2.1 From project-based mitigation to environmental governance

Conventional approaches to transport infrastructure have long been structured around project-bounded impact control, with emphasis on identifying, mitigating, and compensating localized environmental effects. Although this logic remains indispensable within environmental assessment and licensing procedures, its explanatory and regulatory reach becomes limited when the object of concern is a territorially expansive corridor embedded in complex socioecological systems. Recent literature shows that infrastructure impacts in highly sensitive biomes unfold through cumulative, indirect, and path-dependent transformations affecting ecological integrity, land-use dynamics, and institutional capacity (Morrison-Saunders & Sánchez, 2024; Dvořáková *et al*., 2024; Ghijselinck *et al*., 2026). From this perspective, the relevant question is no longer only whether a road segment complies with formal environmental requirements, but whether governance arrangements are capable of preventing structural incompatibilities between infrastructure operation and territorial sustainability. This shift reflects a broader evolution in environmental law, which has long stressed that environmental protection cannot be reduced to isolated authorizations or fragmented administrative acts, since environmental goods are cumulative, interdependent, and often irreducible to sectoral boundaries (Machado, 2024; Leite & Bello Filho, 2004; Sands *et al*., 2018).

2.2 Amazonian highways as corridor-scale socioecological drivers

In the Amazon, roads operate not merely as transport structures, but as vectors of territorial reorganization. They alter accessibility, reshape land values, induce settlement and speculative occupation, intensify forest conversion, and modify hydrological and ecological flows across broad spatial scales. Empirical research has repeatedly shown that transport interventions in the region generate effects that exceed the immediate project surroundings, including indirect deforestation, degradation, fire vulnerability, and fragmentation (Vilela *et al*., 2020; Araujo *et al*., 2025; Matricardi *et al*., 2020; Lapola *et al*., 2023). Road-ecology scholarship reinforces this broader understanding by showing that roads reduce landscape permeability, intensify habitat fragmentation, alter drainage patterns, and disrupt wildlife movement across scales (Bennett, 2017; Xiong *et al*., 2025). The corridor therefore emerges as the relevant analytical unit because it captures the interaction between infrastructure functionality, ecological connectivity, territorial transformation, and governance responses. This perspective also aligns with the notion of a persistent socioecological scar, understood here as a territorial imprint produced by the interaction between road infrastructure and the ecological, hydrological, and social dynamics of a highly sensitive biome. Under this view, roads must be assessed not only by engineering performance or formal mitigation compliance, but by the degree to which they reproduce or reduce structural conditions of socioecological fragility.

2.3 Brazilian Environmental Law and the limits of fragmented regulation

Brazilian Environmental Law contains a sophisticated normative framework for preventive intervention, impact assessment, and public control of environmentally relevant activities. The National Environmental Policy Act established environmental licensing and the review of effectively or potentially polluting activities as central instruments of environmental policy (Brazil, 1981). CONAMA Resolution No. 1/1986 set out the basic criteria and general guidelines for environmental impact assessment, expressly requiring the analysis of alternatives, area of influence, cumulative effects, and monitoring in activities such as highways (CONAMA, 1986). CONAMA Resolution No. 237/1997 further structured environmental licensing as an administrative procedure intended to reconcile technical analysis, institutional control, and environmental feasibility (CONAMA, 1997). In doctrinal terms, such instruments are traditionally understood as preventive legal mechanisms designed to discipline development choices under the constitutional duty of environmental protection (Machado, 2024; Benjamin & Milaré, 1993; Leite & Bello Filho, 2004). However, the existence of legal instruments does not, by itself, ensure adequate corridor-scale governance. Even when cumulative effects are formally recognized, institutional practice often remains centered on the enterprise, the licensing file, and the bounded area of direct influence. In ecologically complex regions such as the Amazon, this may produce a mismatch between the legal form of decision-making and the territorial form of environmental change. Supplementary Law No. 140/2011 strengthened cooperative federalism by distributing environmental administrative competences among federative entities (Brazil, 2011), yet coordination deficits remain relevant whenever environmental liabilities transcend administrative boundaries, involve multiple agencies, or materialize incrementally through land-use feedbacks, fire regimes, hydrological disturbance, and enforcement asymmetries. Legal adequacy, therefore, cannot be reduced to the formal issuance of licenses or to the bounded management of direct impacts. In corridor settings marked by cumulative effects, ecological interdependence, and distributed administrative competences, Brazilian Environmental Law is better understood as imposing at least four connected governance duties: the duty to define the relevant area of influence in territorially coherent terms; the duty to consider cumulative and indirect effects beyond the immediate footprint; the duty to articulate federative and interinstitutional coordination where liabilities exceed a single administrative domain; and the duty to maintain monitoring and adaptive response compatible with evolving corridor conditions. Under this reading, the central legal problem is not the absence of normative instruments, but the gap between formally valid procedures and the territorial intelligibility required for environmentally adequate corridor governance. (Sands *et al.*, 2018; Fisher, 2013; Karkkainen, 2002; Ruhl, 2010).

2.4 Territorial governance and multidimensional environmental diagnosis

If Amazonian highways operate as corridor-scale socioecological drivers and if fragmented regulation struggles to apprehend cumulative territorial dynamics, then a more integrated model of governance becomes necessary. In recent years, the literature on sustainability transitions, ecological infrastructure, and territorial governance has increasingly moved beyond narrow mitigation logic toward approaches concerned with systemic compatibility, resilience, multifunctionality, and adaptive coordination (Brondizio, 2025; Butt *et al*., 2023; Flores *et al*., 2024). Within infrastructure studies, this transition has supported the argument that evaluation should consider not only technical operability, but also the capacity of infrastructure systems to coexist with ecological processes and territorial rights over time.

In the specific case of Amazonian highways, this analytical move supports a regulatory shift from merely containing impact toward diagnosing governance conditions. The relevant question is no longer only whether a project satisfies procedural licensing requirements, but whether the broader corridor is being governed through arrangements capable of linking ecological integrity, infrastructure performance, territorial ordering, and institutional accountability over time. From this perspective, environmental governance should be evaluated through the interaction among at least five interdependent dimensions: ecological integrity, infrastructural adequacy, socioeconomic insertion, social conditions, and institutional capacity. None of these dimensions alone is sufficient to explain corridor performance; taken together, however, they allow diagnosis of where governance failure is concentrated and how environmental fragility is territorially distributed.

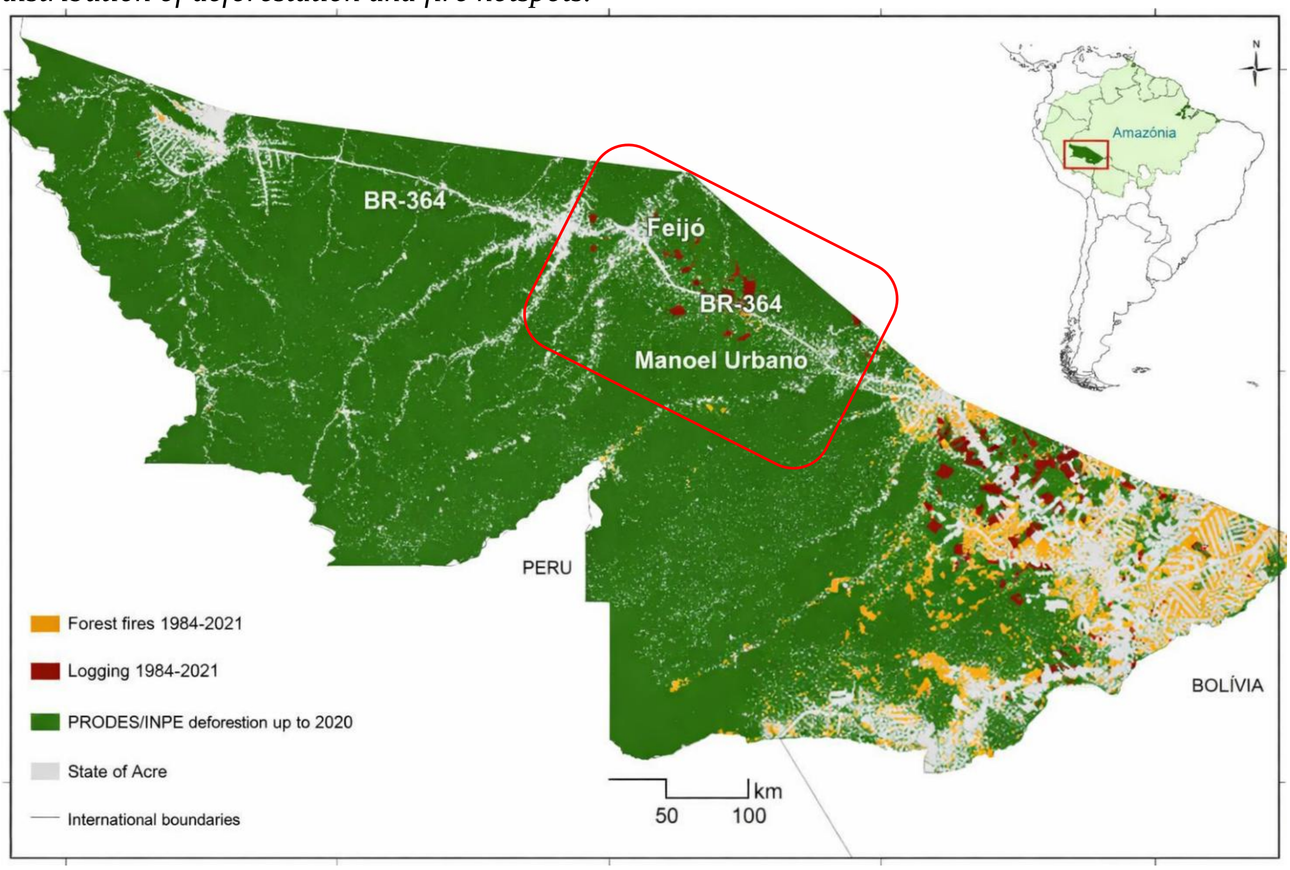
It is precisely within this theoretical horizon that the Amazon Road Sustainability Index (ISRAM) is positioned. Rather than replacing environmental licensing or conventional impact assessment, ISRAM is conceived as a complementary diagnostic framework designed to make visible cumulative liabilities, coordination deficits, and structural incompatibilities that may remain partially obscured under project-centered analysis. Its theoretical foundation lies in the proposition that corridor governance requires multidimensional territorial intelligence. By integrating environmental, technological, economic, social, and institutional indicators, the index seeks to provide an analytically transparent basis for interpreting whether a given corridor operates within a pattern of relative compatibility, structural fragility, or critical socioecological mismatch. In this sense, ISRAM is not a certification tool, but a governance-oriented instrument intended to support legal-institutional reflection on the environmental performance of Amazonian highways.

3 METHODOLOGY

3.1 Study area and case selection

Figure 1

Study area and territorial context of the Manoel Urbano–Feijó segment of BR-364 in Acre, Southwestern Amazon, including the corridor's zone of influence and the spatial distribution of deforestation and fire hotspots.



The empirical application focuses on the Manoel Urbano–Feijó segment of BR-364, in the state of Acre, Southwestern Brazilian Amazon. The case was selected because it combines logistical relevance, chronic technical deficiencies, environmental vulnerability, and frontier pressures, making it suitable for testing a corridor-scale diagnostic framework. As shown in Figure 1, the study area was defined not as a narrow engineering footprint, but as a socioecological-territorial corridor, including its broader zone of influence and the surrounding pattern of deforestation pressure and fire occurrence. This definition is consistent with the article's legal-institutional premise that environmental governance in Amazonian highways cannot be adequately understood through project-bounded assessment alone. The corridor is therefore treated as the relevant unit for integrated diagnosis of ecological, infrastructural, social, economic, and institutional conditions.

3.2 Analytical architecture of ISRAM

ISRAM was constructed as a composite diagnostic framework organized around five analytical dimensions: Environmental, Technological, Economic, Social, and Institutional. Composite indicators are particularly appropriate when the phenomenon under analysis is multidimensional and cannot be satisfactorily represented by a single variable, provided that construction rules are explicit, interpretable, and methodologically auditable (Saisana *et al*., 2005; OECD/JRC, 2008). In the present study, the framework comprises 25 indicators distributed across the five dimensions in order to capture corridor-scale ecological integrity, infrastructural adequacy, territorial functionality, social conditions, and governance capacity. To preserve concision in the main manuscript, Table 1 presents only the analytical structure of the five dimensions and the number of indicators assigned to each one, while the full metadata, source documentation, and indicator allocation are reported in the Supplementary Material.

Table 1

Analytical structure of ISRAM

Dimension	Analytical focus	Number of indicators
Environmental	Ecological integrity and environmental pressure	6
Social	Human well-being and social vulnerability	5
Economic	Territorial functionality and economic support conditions	4
Institutional	Governance, management, and institutional capacity	5
Technological	Infrastructure adequacy and operational condition	5

3.3 Data sources and evidence triangulation

Data collection followed a mixed-evidence triangulation protocol designed to reduce single-source bias and strengthen diagnostic consistency, as recommended in case-based and mixed-method research (Patton, 1999; Creswell & Plano Clark, 2018). Three forms of evidence were combined: documentary evidence from official institutional sources; spatial evidence used to situate the corridor within its broader territorial context; and field-based technical observations used to verify corridor-wide operational features not fully retrievable from secondary datasets alone. In the present application, field observation served a confirmatory and classificatory function for corridor-wide indicators related to platform width, right-of-way condition, surfacing type, access control, signage, wildlife-crossing structures, fencing, and encroachment control, always in conjunction with DNIT technical records and project-related documentation rather than as a standalone source. All variables refer to the empirical application year adopted in the framework and were harmonized at corridor scale.

3.4 Standardization, scoring, and aggregation

Because the indicators are heterogeneous in scale and unit, all variables were standardized to a common score ranging from 0 to 1,000, following a classification logic consistent with composite indicator construction and transparent benchmarking procedures (Saisana *et al*., 2005; OECD/JRC, 2008). Performance was interpreted through seven ordered classes—Critical, Very Bad, Bad, Basic, Good, Very Good, and

Regenerative—designed as diagnostic categories for corridor-scale interpretation rather than as universal ecological or engineering thresholds. Indicator directionality was preserved so that higher scores represent more favorable corridor conditions and lower scores indicate greater structural fragility.

The threshold logic followed three distinct calibration strategies, detailed in the Supplementary Material: normative or technical-reference thresholds for infrastructure and service-related indicators; graduated ordinal thresholds for corridor-management features whose empirical meaning is better captured by incremental presence or complexity; and empirical distribution or policy-reference thresholds for territorial and municipal indicators derived from official datasets. This choice was intended to maximize interpretability and transparency in the BR-364 application while avoiding the false impression that heterogeneous variables could be meaningfully standardized through a single uniform rule.

In the baseline model, indicator scores were first aggregated by arithmetic mean within each dimension, and the overall ISRAM score was then calculated as the arithmetic mean of the five dimensional scores, with equal weights assigned to all dimensions. Equal weighting was adopted as a transparent and least-arbitrary starting assumption in the absence of a sufficiently defensible ex ante basis for assigning systematic priority to one dimension over the others. The full scoring matrix, threshold logic, and mathematical specification are reported in the Supplementary Material.

3.5 Replicability, calibration, and robustness

The present application was designed to ensure procedural replicability and case-based diagnostic plausibility, rather than to claim universal calibration. The analytical architecture of ISRAM is transferable, but future applications to other Amazonian corridors may require context-sensitive recalibration of selected indicators, thresholds, and reference values. To test whether the BR-364 diagnosis depended excessively on baseline modeling choices, a structured sensitivity analysis was conducted, as recommended in the literature on composite indices (Saisana *et al*., 2005; OECD/JRC, 2008). Three sources of methodological variation were examined: alternative dimensional weights, modest shifts in classification thresholds, and non-linear aggregation using the geometric mean. The purpose of this step was not to replace the baseline model, but to verify whether the overall performance class and the main dimensional fragility pattern remained stable under plausible alternative assumptions. The full rationale, tested scenarios, equations, and results of the robustness procedure are presented in the Supplementary Material.

3.6 Methodological output and legal-regulatory interpretation

The methodological output of ISRAM is a corridor-scale diagnostic profile composed of: (i) one overall score on a 0–1,000 scale; (ii) five dimensional scores; and (iii) an interpretive reading of whether fragility is concentrated, diffuse, or structurally asymmetric across dimensions. Legally, this output is not intended to replace licensing, EIA, or project appraisal. Its function is narrower and complementary: to provide a structured territorial diagnostic capable of informing whether existing governance arrangements are sufficiently responsive to cumulative effects, cross-scalar ecological interaction, federative coordination demands, and adaptive monitoring duties. In this sense, ISRAM operates not as a certification device, but as a diagnostic aid for assessing the legal-institutional adequacy of corridor governance under conditions that may be only partially captured by project-bounded procedures. Detailed thresholds, indicator metadata, empirical application records, and robustness tests are reported in the Supplementary Material.

4 RESULTS

4.1 Overall ISRAM score

The empirical application of ISRAM to the Manoel Urbano–Feijó segment of BR-364 yielded a global score of 260.5/1,000, placing the corridor in the Bad category according to the classification matrix adopted in this study. The result indicates marked corridor-scale underperformance in a highly sensitive Amazonian setting and suggests that the segment cannot be interpreted as a stable axis of environmentally compatible territorial integration. Rather than expressing an isolated maintenance deficit, the score reflects cumulative weaknesses distributed across environmental, technological, economic, social, and institutional domains, thus requiring disaggregated interpretation.

4.2 Dimensional decomposition and identification of the fragility core

The disaggregated reading of ISRAM shows that corridor fragility is not evenly distributed across the five dimensions. Instead, performance is markedly asymmetric: Social = 490.0, Institutional = 420.0, Economic = 237.5, Technological = 80.0, and Environmental = 75.0. This internal contrast is analytically decisive because it reveals that the corridor's critical condition is not driven by generalized but homogeneous low performance. The most severe deficits are concentrated in the Technological and Environmental dimensions, both of which remain at extremely low levels relative to their maximum possible values. This convergence constitutes the central empirical pattern of the application and suggests that corridor-scale underperformance is structurally anchored in the interaction between infrastructural inadequacy and ecological incompatibility under tropical forest conditions. By contrast, the Social and Institutional dimensions, although far from satisfactory, indicate the presence of limited residual capacities that do not suffice to offset the dominant fragility pattern.

Table 2

ISRAM dimensional results for the Manoel Urbano–Feijó segment (BR-364/AC)

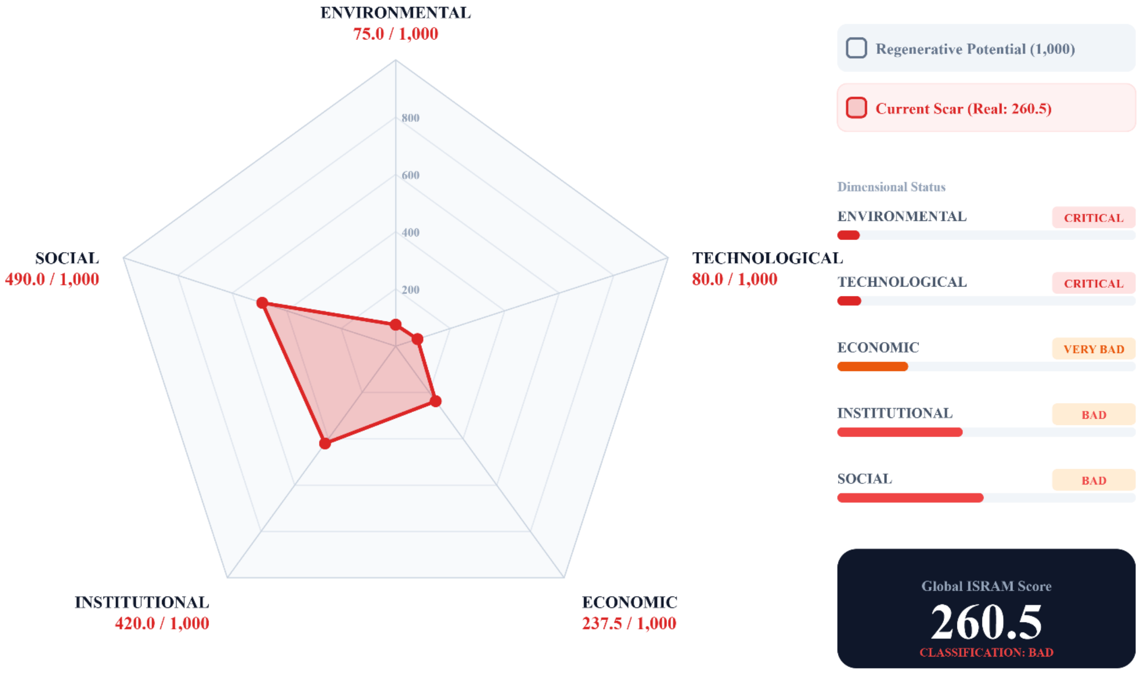
Dimension	Score (0–1,000)	% of dimension maximum	Synthetic diagnostic reading
Social	490.0	49.0%	Low-intermediate performance; partial social capacity present, but insufficient to sustain territorial resilience.
Institutional	420.0	42.0%	Limited governance and management responsiveness; insufficient for adaptive coordination in a highly sensitive corridor.
Economic	237.5	23.8%	Low systemic efficiency; signs of cost externalization and weak life-cycle sustainability.
Technological	80.0	8.0%	Severe technical-functional inadequacy; low fit between design and operational conditions and the Amazonian environment.
Environmental	75.0	7.5%	Critical ecological underperformance; conditions incompatible with maintaining corridor-scale socioecological integrity.

4.3 Visual synthesis of dimensional asymmetry

Figure 2 visually synthesizes the corridor’s dimensional profile and makes the asymmetry of the diagnosis immediately perceptible. Instead of a relatively balanced polygon, the radar chart contracts sharply along the Technological and Environmental axes, while the Social and Institutional axes remain comparatively less compressed and the Economic axis occupies an intermediate but still weak position. This visual structure is scientifically relevant because it demonstrates that the corridor does not merely display generalized low performance. Rather, it exhibits a concentrated fragility core, located precisely at the intersection between technical inadequacy and environmental incompatibility. The main contribution of this result lies in preserving dimensional differentiation instead of collapsing heterogeneous conditions into an undifferentiated average. By doing so, the framework identifies where corridor fragility is structurally anchored and prepares the analytical basis for the next section, which discusses why project-centered or excessively compensatory assessments may underdiagnose critical territorial incompatibilities in Amazonian highways.

Figure 2

Dimensional profile of ISRAM for the Manoel Urbano–Feijó segment of BR-364, showing the concentrated technological–environmental fragility core.



4.4 Robustness of the empirical diagnosis

To verify whether the diagnosis depended excessively on baseline modeling assumptions, the framework was subjected to sensitivity analysis under three alternative specifications reported in the Supplementary Material. The substantive interpretation remained stable across all scenarios. Under alternative weighting with greater emphasis on the Technological and Environmental dimensions, the final score decreased to 206.75, but the corridor remained in the Bad class. Under modest threshold adjustment, the score remained 260.50, with no change in qualitative classification. Under geometric aggregation, the score declined to 196.54, shifting to Very Bad, yet the same technological–environmental fragility core was preserved. These results indicate that the central empirical interpretation is not an artifact of a single arbitrary modeling choice. Instead, the diagnosis of low corridor compatibility and concentrated dimensional fragility remains materially stable under plausible variation in weighting, thresholds, and aggregation logic. Detailed robustness results are provided in the Supplementary Material.

5 DISCUSSION

5.1 Interpreting corridor fragility beyond a low aggregate score

The results obtained for the Manoel Urbano–Feijó segment of BR-364 should not be interpreted as a mere expression of generalized underperformance or deferred maintenance. Their principal analytical significance lies in the internal structure of the diagnosis. The overall score of 260.5/1,000 is relevant, but the real contribution of the application emerges from the dimensional asymmetry identified by ISRAM. Rather than revealing homogeneous weakness across all domains, the framework exposes a concentrated fragility core located in the Technological and Environmental dimensions, while the Social and Institutional dimensions remain comparatively less degraded, though still insufficient to sustain corridor resilience. This pattern indicates that the corridor's low performance is not simply additive; it is structurally organized around the interaction between technical inadequacy and ecological incompatibility.

This finding is important because it moves the analysis beyond aggregate ranking logic. A single low score may describe poor performance, but it does not explain how fragility is produced, where it is concentrated, or which governance functions are failing most severely. By preserving dimensional decomposition, ISRAM makes it possible to distinguish between diffuse underperformance and structurally concentrated incompatibility. In the present case, the critical point is not that every dimension performs equally badly, but that the two dimensions most directly associated with long-term territorial viability—environmental integrity and infrastructural adequacy—form the weakest part of the corridor system. In practical terms, this means that the corridor is not merely suboptimal; it is misaligned with the ecological and operational conditions of a highly sensitive Amazonian environment.

From a governance perspective, this asymmetry is especially revealing. If environmental fragility were severe but technological conditions were robust, one could at least hypothesize a corridor capable of operational continuity while awaiting ecological compensation or restoration. Conversely, if technical performance were relatively satisfactory and environmental pressure were moderate, adaptive management could plausibly correct residual incompatibilities. The diagnosis produced here is more problematic because it indicates simultaneous weakness in the two domains that most directly condition corridor durability. The result is a pattern of mutually reinforcing fragility in which poor infrastructural performance aggravates environmental vulnerability, while environmental instability further undermines the functional and regulatory adequacy of the corridor.

5.2 The technological–environmental core as a governance problem

The concentration of fragility in the Technological and Environmental dimensions should be interpreted not merely as an empirical pattern, but as a governance problem. In Amazonian highways, technical inadequacy is never an isolated engineering issue. Road surface instability, insufficient drainage, limited protective structures, weak adaptation to hydrological conditions, and low ecological permeability interact directly with erosion, habitat fragmentation, altered runoff, fire vulnerability, and declining landscape connectivity. Under such conditions, infrastructure ceases to function as a protective interface between circulation and ecological integrity and instead becomes a vector of cumulative territorial incompatibility.

This is the central meaning of the technological–environmental core identified in the BR-364 corridor. The problem is not only that environmental conditions are poor or that technological performance is deficient when considered separately. The critical issue is that both dimensions deteriorate simultaneously and reinforce one another. Weak infrastructural adequacy intensifies ecological disturbance, while ecological instability, in turn, further reduces corridor reliability, maintenance efficiency, and territorial resilience. What emerges is a mutually reinforcing pattern of fragility in which technical and environmental deficits cannot be meaningfully governed in isolation.

This finding is especially relevant in tropical forest settings, where infrastructure performance depends on long-term compatibility with hydrological dynamics, ecological connectivity, and biome sensitivity. A road may remain operational in a narrow logistical sense and still perform poorly from an environmental-governance perspective if its technical configuration reproduces instability, fragmentation, and recurrent territorial liabilities. In this context, technological adequacy must be interpreted not only as engineering functionality, but as the capacity of infrastructure to operate without persistently amplifying socioecological disruption.

The same reasoning applies to the Environmental dimension. Its critically low score does not simply register isolated ecological pressures; it indicates that the corridor operates under conditions incompatible with maintaining socioecological integrity at territorial scale. This interpretation is consistent with the literature showing that Amazonian road expansion is associated not only with direct deforestation, but also with degradation, fire exposure, edge effects, and broader ecological destabilization. The value added by ISRAM lies in showing how these processes are not externalities surrounding the corridor, but part of the same structural configuration that also includes technological inadequacy.

From a governance standpoint, the relevance of this result is straightforward. Where technological and environmental fragilities converge, the corridor’s condition cannot be adequately interpreted through sectoral or compartmentalized responses alone. What is required is a governance perspective capable of reading infrastructure, ecological processes, and territorial risk as interdependent components of the same regulatory problem. In this sense, the technological–environmental core identified in BR-364 should be understood as evidence that corridor underperformance is rooted in a persistent mismatch between infrastructure design and operation, biome conditions, and the institutional capacity to govern their interaction over time.

5.3 Brazilian Environmental Law and the limits of project-bounded governance

From the standpoint of Brazilian Environmental Law, the findings do not suggest the irrelevance of existing legal instruments. On the contrary, they confirm their continuing necessity. Environmental licensing, environmental impact assessment, monitoring obligations, and administrative control remain indispensable mechanisms for preventing harm and disciplining development choices. The National Environmental Policy, CONAMA Resolution No. 1/1986, and CONAMA Resolution No. 237/1997 provide a relevant normative basis for environmental oversight, including the analysis of alternatives, area of influence, cumulative effects, and follow-up. Likewise, Supplementary Law No. 140/2011 offers a cooperative framework for the distribution of environmental administrative competences. The legal architecture, therefore, is not trivial, nor can it be dismissed as normatively empty.

The problem revealed by the present study lies elsewhere. It concerns the difficulty of making that legal architecture fully operative when the environmental object to be governed is not a discrete enterprise, but a territorially extensive, ecologically sensitive, and institutionally distributed corridor. Even where legal provisions formally require cumulative analysis and environmental monitoring, administrative practice often remains centered on licensing files, bounded areas of influence, and segmented institutional routines. Under such conditions, the corridor may be procedurally addressed without being substantively understood. The present findings reinforce the view that formal compliance and territorial adequacy are not equivalent categories. A road may be situated within a recognizable licensing framework and still operate under conditions of severe socioecological mismatch.

This distinction is especially important for a legal journal. The contribution of the article is not to oppose environmental licensing, but to demonstrate the limits of an exclusively project-bounded reading of environmental legality in Amazonian road governance. When impacts unfold cumulatively, through feedbacks involving land use, ecological connectivity, fire exposure, hydrological disturbance, and uneven institutional capacity, the relevant legal question becomes broader than whether licensing occurred. It becomes necessary to ask whether the governance arrangement is capable of producing corridor-scale environmental intelligibility. In that sense, the present study supports a more demanding understanding of legality—one that includes not only procedural regularity, but also the practical capacity to diagnose, monitor, and respond to territorially distributed harm.

5.4 ISRAM as a complementary instrument for legal-institutional interpretation

Within this context, ISRAM should be understood as a complementary diagnostic tool for legal-institutional interpretation rather than as a substitute for environmental licensing or impact assessment. Its contribution lies in making visible patterns of fragility that may remain diluted when analysis is fragmented across separate procedures, sectors, or agencies. By integrating environmental, technological, economic, social, and institutional dimensions within a single corridor-scale reading, the framework helps identify whether the dominant problem is ecological, technical, managerial, socioeconomic, or structurally hybrid.

Its legal-regulatory usefulness lies in supporting environmental monitoring, improving the interpretation of cumulative effects, informing adaptive coordination, and broadening accountability through auditable multidimensional assessment. At the same time, methodological caution remains essential: ISRAM does not produce legal effects automatically, does not replace technical licensing procedures, and does not claim universally fixed ecological thresholds. Its present application is case-based and diagnostically oriented.

Yet this does not diminish its legal-institutional relevance. Under conditions of complexity, uncertainty, and cumulative harm, instruments that improve territorial intelligibility form part of the practical infrastructure of sound environmental governance. In this sense, ISRAM is relevant not because it displaces existing legal instruments, but because it expands the interpretive capacity through which corridor-scale environmental problems can be identified, understood, and more effectively governed.

5.5 Scientific contribution and implications for Amazonian highway governance

The principal scientific contribution of this article lies in demonstrating that the environmental condition of Amazonian highways cannot be adequately captured by generic sustainability language, isolated project metrics, or undifferentiated aggregate diagnosis. The BR-364 case shows that corridor underperformance may be structurally concentrated in specific dimensions whose interaction is more informative than the final score alone. By identifying a technological–environmental fragility core that remains stable across alternative modeling scenarios, the study adds a more precise and operational layer to debates on infrastructure, environmental degradation, and territorial governance in the Amazon.

Its legal-institutional contribution is equally significant. The article shows that a more demanding model of environmental governance is required for Amazonian highways, one capable of combining licensing, cumulative analysis, territorial planning, and adaptive interinstitutional coordination. In that sense, the value of ISRAM is not merely methodological. It lies in offering a structured basis for understanding how corridor-scale governance can become more intelligible, more transparent, and more responsive to the multidimensional nature of territorial harm. This contribution is particularly relevant in the Brazilian Amazon, where legal instruments already exist, but where the central challenge increasingly concerns the quality of their territorial articulation and practical effectiveness.

Taken together, the discussion suggests that the future of Amazonian highway governance depends less on multiplying formal procedures than on improving the capacity of legal and institutional arrangements to read the corridor as a complex territorial system. The BR-364 case does not support simplistic claims of total regulatory failure, nor does it justify purely compensatory optimism. What it reveals is something more precise and more consequential: a corridor whose low overall performance is anchored in a persistent mismatch between infrastructural functioning, environmental integrity, and governance capacity. This is precisely the kind of mismatch that environmental law must become better equipped to diagnose and govern.

6 CONCLUSIONS

This article examined the environmental governance condition of the Manoel Urbano–Feijó segment of BR-364 through the application of ISRAM, a multidimensional corridor-scale diagnostic framework. The results showed low overall performance and, more importantly, a concentrated fragility core in the Environmental and Technological dimensions, indicating a persistent socioecological mismatch between infrastructural functioning, ecological integrity, and governance capacity in a highly sensitive Amazonian setting. More than a descriptive score, this pattern reveals that corridor fragility is distributed asymmetrically across interdependent dimensions and therefore cannot be adequately interpreted through project-bounded readings alone.

From a legal-institutional perspective, the findings do not diminish the relevance of Brazilian environmental licensing and impact assessment. On the contrary, they reinforce their continuing centrality while exposing the limits of interpretations confined to formally licensed footprints when the object to be governed is a cumulative, territorially extended, and ecologically interconnected corridor. In this context, legal adequacy cannot be understood as satisfied solely by the formal existence of administrative procedures. It must also be assessed in light of whether governance arrangements are capable of defining area of influence in territorially coherent terms, accounting for cumulative and indirect effects, articulating federative and interinstitutional coordination, and maintaining adaptive monitoring compatible with changing corridor conditions.

Methodologically, the article offers a transparent and replicable framework for identifying how governance-critical weaknesses are distributed across corridor dimensions. ISRAM is not proposed as a substitute for licensing, EIA, or project appraisal, but as a complementary territorial diagnostic capable of informing the legal-institutional interpretation of corridor conditions under cumulative and cross-scalar pressures. The broader implication is not that Brazilian Environmental Law lacks instruments, but that environmentally adequate Amazonian highway governance requires a more demanding territorial reading of duties already embedded in the legal order. For that reason, the article concludes that the governance of Amazonian highways should be evaluated not only by the procedural validity of authorization, but by the capacity of legal-institutional arrangements to govern road corridors as territorially extended socioecological systems.

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Authors' Contribution

All authors contributed equally to the development of this article.

Data availability

All datasets relevant to this study's findings are fully available within the article.

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