

ENVIRONMENTAL GOVERNANCE OF AMAZONIAN HIGHWAYS

GESTÃO AMBIENTAL DAS ESTRADAS DA AMAZÔNIA

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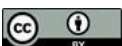
The authors declare that there is no conflict of interest

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 SUPPLEMENTARY MATERIAL FOR: ENVIRONMENTAL GOVERNANCE OF AMAZONIAN HIGHWAYS

This Supplementary Material provides the methodological documentation and robustness checks supporting the application of the Index of Sustainability of Amazonian Roads (ISRAM) to the BR-364 corridor between Manoel Urbano and Feijó. It includes the operational logic of the framework, indicator metadata, classification criteria, detailed empirical application, and sensitivity analysis under alternative specifications. The purpose of this document is to ensure transparency, auditability, replicability, and context-sensitive transferability while preserving the concision of the main manuscript. All data sources used in the ISRAM application are derived from publicly available institutional datasets and complemented by field-based technical assessments conducted along the BR-364/AC corridor. In the present article, ISRAM is interpreted as a corridor-scale diagnostic framework for assessing the regulatory and socioecological condition of Amazonian highway corridors under a transition from mitigation-centered assessment toward regenerative governance.

2 PART I. SUPPLEMENTARY METHODOLOGICAL DOCUMENTATION

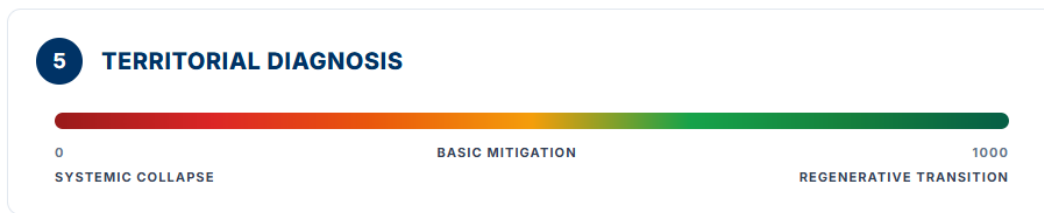
Figure S1

Methodological flowchart for the construction and empirical application of ISRAM as a corridor-scale diagnostic framework for the regulatory and socioecological assessment of Amazonian highway corridors.

METHODOLOGICAL DESIGN: ISRAM INDEX

Structural workflow for the construction and evaluation of the Amazon Road Sustainability Index, based on composite indicator guidelines (OECD, 2008).





The methodological logic summarized in Figure S1 is detailed below through the conceptual structure of the framework, the criteria for indicator selection, and the operational rules used for scoring and aggregation. Together, these elements define the analytical basis of ISRAM as a multidimensional diagnostic tool for corridor-scale regulatory and socioecological assessment.

2.1 Section S1 Conceptual and operational structure of Isram

The Index of Sustainability of Amazonian Roads (ISRAM) is a multidimensional diagnostic framework designed to assess the regulatory and socioecological condition of highway corridors in tropical forest regions. Rather than evaluating infrastructure solely through engineering efficiency or aggregate sustainability scores, the framework seeks to identify structural conditions of corridor-scale fragility, compatibility, and territorial misalignment. ISRAM is organized around five analytical dimensions—Environmental, Social, Economic, Institutional, and Technological—each represented by a set of operational indicators derived from publicly available datasets and territorial statistics. Together, the 25 indicators capture key aspects of ecological integrity, human well-being, territorial functionality, governance capacity, and infrastructural adequacy at corridor scale.

The framework operates through three main analytical steps. First, indicators are standardized and classified according to performance thresholds derived from empirical benchmarks and policy-relevant reference values. Second, indicator scores are aggregated within each dimension to produce dimensional performance values. Third, the five dimensional scores are aggregated to generate the overall ISRAM index for the corridor. The resulting diagnostic profile enables the identification of asymmetries across

dimensions and highlights structural fragilities that may not be visible through single-metric assessments.

2.2 S1.1 Analytical dimensions and indicator selection criteria

The five analytical dimensions adopted in ISRAM were selected to represent interdependent components of corridor-scale regulatory and socioecological condition. Environmental indicators capture pressures affecting ecological integrity, including forest loss, fire exposure, and landscape disturbance. Social indicators represent conditions related to human well-being, including public health and vulnerability. Economic indicators reflect the productive structure and territorial economic dynamics associated with the corridor. Institutional indicators assess governance capacity and the presence of territorial management structures. Technological indicators evaluate the adequacy of road infrastructure and associated systems, including maintenance conditions, drainage structures, and operational safety.

Indicator selection followed four main criteria: conceptual relevance to corridor-scale territorial dynamics; empirical observability through reliable datasets; territorial applicability to Amazonian infrastructure systems; and interpretability within a multidimensional diagnostic framework. The final indicator set was designed to balance ecological, social, economic, institutional, and infrastructural variables while maintaining operational feasibility and data transparency. As operationalized in the present application, ISRAM comprises 25 indicators distributed asymmetrically across the five dimensions: Environmental (6), Social (5), Economic (4), Institutional (5), and Technological (5).

2.3 S1.2 Indicator standardization, classification rationale, and empirical application

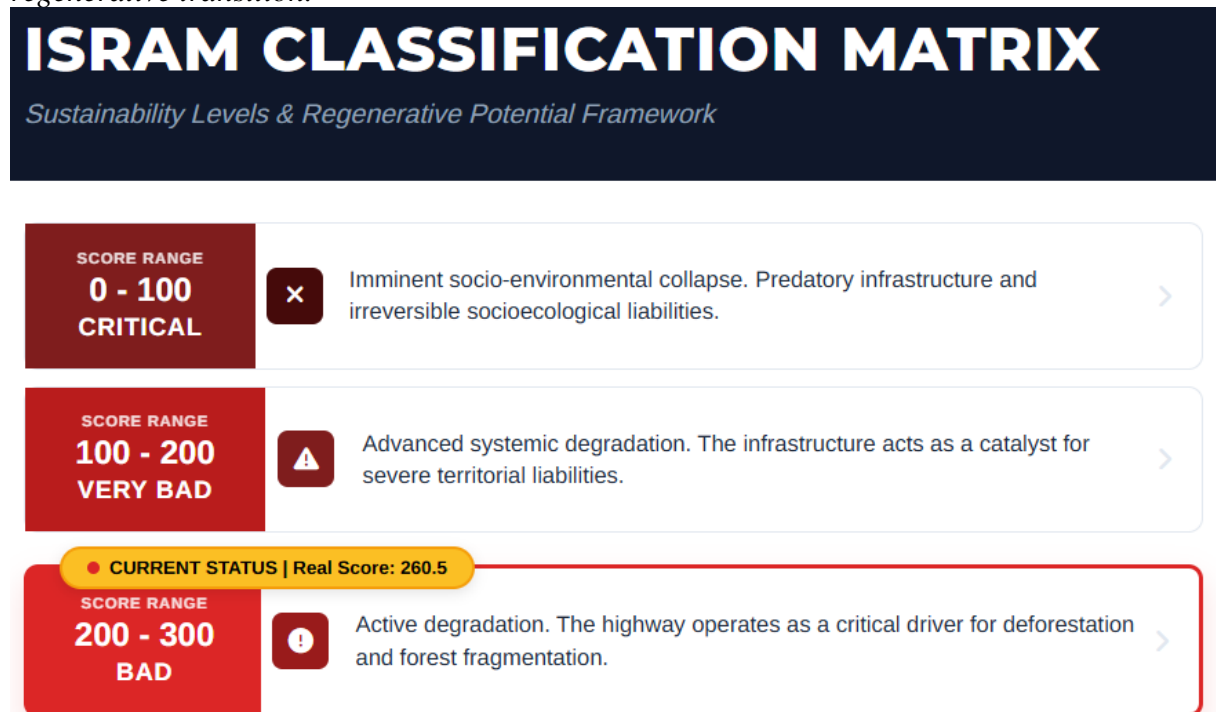
Because the 25 ISRAM indicators differ in scale, unit, and empirical meaning, all variables were standardized to a common diagnostic range from 0 to 1,000. This standardization was designed to permit cross-dimensional comparability while preserving

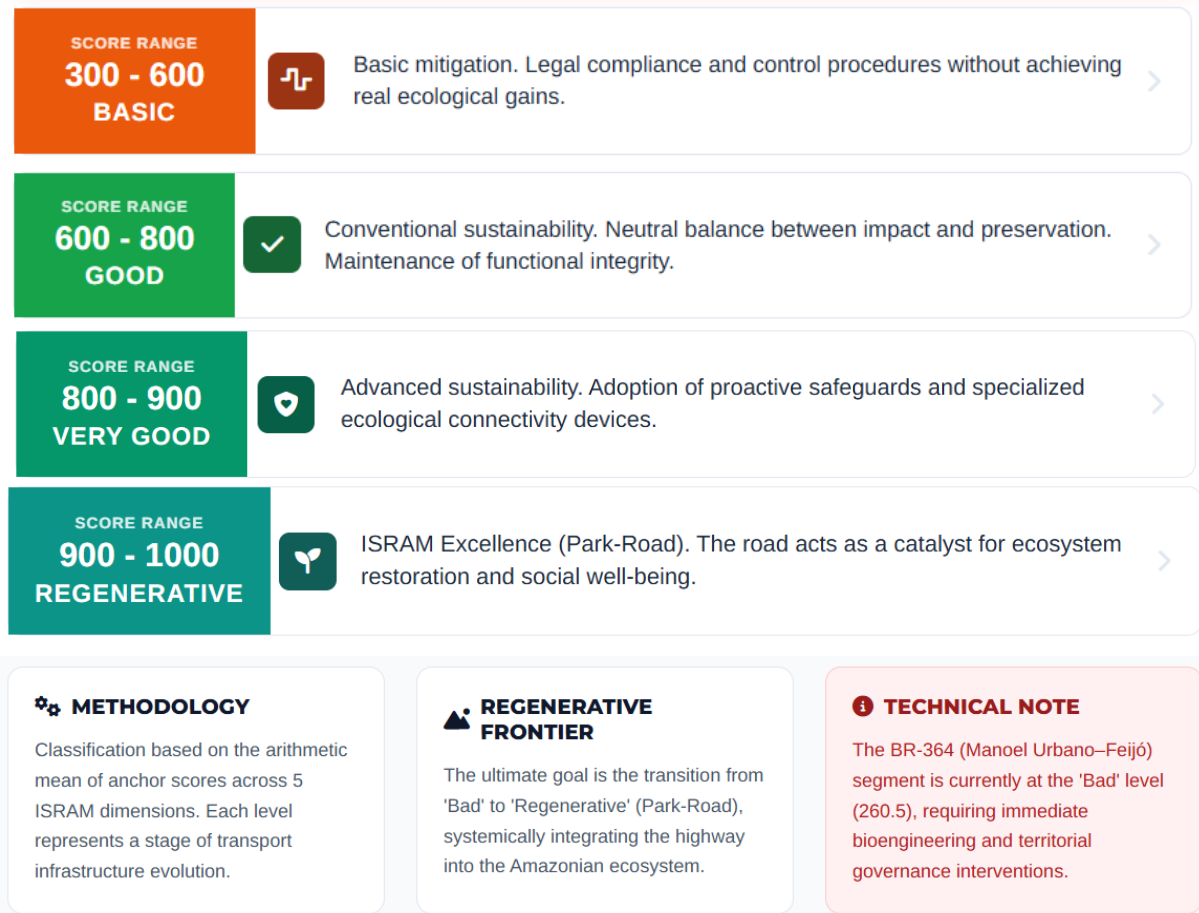
interpretability at corridor scale. Higher scores indicate more favorable regulatory and socioecological conditions, whereas lower scores indicate greater fragility. In analytical terms, the objective of standardization is not to erase the heterogeneity of the original variables, but to translate them into a common evaluative language that allows multidimensional aggregation and structured comparison across dimensions.

The standardized values were interpreted through seven ordered classes: Critical, Very Bad, Bad, Basic, Good, Very Good, and Regenerative. These classes should be understood as diagnostic categories for corridor-scale interpretation rather than as universal biophysical thresholds. Their purpose is to distinguish gradients of compatibility, fragility, and territorial performance in a transparent and analytically consistent manner. In the present application, the classification matrix was calibrated to support the BR-364 corridor diagnosis and to make explicit the interpretive logic through which raw observed values were translated into standardized scores.

Figure S2

ISRAM classification matrix, showing the seven interpretive classes used to distinguish corridor-scale socioecological performance gradients from critical fragility to regenerative transition.





Note: *The classes shown in Figure S2 are interpretive categories designed to support transparent corridor-scale diagnosis in the present BR-364 application. They should not be read as universally fixed thresholds. In future applications to other Amazonian corridors, selected thresholds may require context-sensitive recalibration depending on corridor-specific ecological, infrastructural, and governance conditions.*

Indicator directionality was preserved throughout the scoring process. Variables for which higher empirical values represent better corridor conditions were standardized positively, whereas variables for which higher empirical values indicate greater fragility were standardized negatively. This distinction is essential for replicability, because it ensures that the final scores consistently represent the same analytical direction across all dimensions. The full list of indicators, empirical focus, primary data sources, and web access points is provided in Table S1.

Table S1

Indicator structure, metadata, and primary sources of the 25 ISRAM indicators used in the corridor-scale regulatory and socioecological diagnostic framework.

ITEMS	INDICATORS	PRIMARY SOURCE / DATASET (2020)	WEB ADDRESS / INSTITUTIONAL ACCESS
ENVIRONMENTAL DIMENSION			
1	Presence of wildlife crossings	DNIT technical records and field survey (2020)	-
2	Presence of protective fencing (%)	DNIT technical records and field survey (2020)	-
3	Fire hotspots during the critical (driest) month	Government of the State of Acre (2020)	http://semapi.acre.gov.br/
4	Distance from the project corridor to Indigenous Land (km)	National Foundation for Indigenous Peoples (FUNAI, 2020)	https://www.gov.br/funai/pt-br/atuacao/terras-indigenas/geoprocessamento-e-mapas
5	Sustainable Cities Development Index (IDSC)	Sustainable Cities Institute (ICS, 2020)	https://www.cidadessustentaveis.org.br/paginas/idsc-br
6	Greenhouse gas emissions (tCO ₂ e per capita)	Greenhouse Gas Emissions Estimation System (SEEG, 2020)	https://plataforma.seeg.eco.br/total_emission
SOCIAL DIMENSION			
1	Final Synthetic Indicator (ISF) – Primary Health Care	Ministry of Health of Brazil (2020)	https://sisaps.saude.gov.br/painelsaps/isf
2	Basic Education Development Index (IDEB) – early grades	Brazilian Institute of Geography and Statistics (IBGE, 2020)	https://cidades.ibge.gov.br/
3	Infant mortality (deaths per 1,000 live births)	Brazilian Institute of	https://cidades.ibge.gov.br/

		Geography and Statistics (IBGE, 2020)	
4	Life expectancy at birth (years)	Federation of Industries of the State of Acre (FIEAC, 2020)	http://observatoriodoacre.org.br/indicadores
5	Homicide rate (per 100,000 inhabitants)	Institute for Applied Economic Research (IPEA, 2020)	https://www.ipea.gov.br/atlasviolencia/dados-series/20
ECONOMIC DIMENSION			
1	Average monthly wage of formally employed workers	Brazilian Institute of Geography and Statistics (IBGE, 2020)	https://cidades.ibge.gov.br/
2	GDP per capita / 1,000 (BRL)	Brazilian Institute of Geography and Statistics (IBGE, 2020)	https://cidades.ibge.gov.br/
3	Employed population (%)	Brazilian Institute of Geography and Statistics (IBGE, 2020)	https://cidades.ibge.gov.br/
4	Mobile phone access density (subscriptions per 100 inhabitants)	National Telecommunications Agency (ANATEL, 2020)	http://informacoes.anatel.gov.br/painéis/aceessos/
INSTITUTIONAL DIMENSION			
1	Right-of-way encroachment control	DNIT technical records and field survey (2020)	-
2	Presence of an environmental enforcement checkpoint	Government of the	https://imac.ac.gov.br/web/

		State of Acre (2020)	
3	Presence of a wildfire response unit	Government of the State of Acre (2020)	https://imac.ac.gov.br/web/
4	Access to water supply services	Water and Sanitation Institute (IAS, 2020)	https://www.aguaesaneamento.org.br/municipios-e-saneamento/
5	Access to solid waste collection services	Water and Sanitation Institute (IAS, 2020)	https://www.aguaesaneamento.org.br/municipios-e-saneamento/
TECHNOLOGICAL DIMENSION			
1	Highway platform width (m)	DNIT technical records and field survey (2020)	-
2	Right-of-way width (m)	DNIT technical records and field survey (2020)	-
3	Pavement sustainability / service life	DNIT technical records and field survey (2020)	-
4	Highway access control	DNIT technical records and field survey (2020)	-
5	Educational and guidance signage	DNIT technical records and field survey (2020)	-

Note: The indicator set is organized into five analytical dimensions—Environmental, Social, Economic, Institutional, and Technological. Variables were selected according to conceptual relevance, empirical observability, territorial applicability, and interpretability within the diagnostic framework. Indicator directionality was explicitly preserved in the standardization process. Indicators for which higher empirical values correspond to better corridor conditions were treated under a “higher is better” logic, whereas indicators for which higher empirical values represent greater fragility were treated under a “lower is better” logic. Replication of the present BR-364 application therefore requires that each indicator be interpreted jointly with its directionality and the corresponding scoring thresholds defined in Table S2.

The scoring thresholds used to convert empirical observations into ISRAM values are presented in Table S2. Threshold calibration did not follow a single rule for all indicators. In the present application, three logics were combined: (i) technical-reference thresholds for infrastructural variables whose interpretation depends on engineering or service-condition parameters; (ii) ordinal gradation thresholds for management and protection features expressed by cumulative levels of provision or control; and (iii) empirical-policy thresholds for territorial indicators derived from official public datasets, using value bands with diagnostic relevance for the BR-364 context. This mixed calibration strategy was adopted because the indicator set includes both continuous and categorical variables and because interpretability at corridor scale was prioritized over artificial metric uniformity. Rather than imposing rigid universal calibration, Table S2 makes explicit the rules through which heterogeneous variables were transformed into standardized corridor-scale diagnostic inputs for the BR-364 application.

Table S2

Classification matrix by performance bands and anchor scores (0–1,000) used in the present ISRAM application.

Indicators (unit)	Classification of indicators							
	Critical (0–100)	Very Bad (100–200)	Bad (200–300)	Basic (300–600)	Good (600–800)	Very Good (800–900)	Regenerative (900–1,000)	
	0	15	2	450	7	8	1	
1. Highway platform width (m)	$m < L \leq 25$	$m < L \leq 25$ m	$8 m < L \leq 20$ m	$< L \leq 18$ m	$4 m < L \leq 16$ m	$2 m < L \leq 14$ m	≤ 12 m	
2. Right-of-way width (m)	$L \geq 100$ m	$0 m < L \leq 250$ m	$50 m < L \leq 500$ m	$< L \leq 750$ m	$50 m < L \leq 1,000$ m	$,000 m < L \leq 2,000$ m	$> 2,000$ m	
3. Pavement sustainability / service life	No surfacing (unpaved)	Stabilized-soil base & subbase + TSD (surface treatment)	Stabilized-soil base & subbase + CBUQ (hot-mix asphalt)	Crushed-stone base & subbase + CBUQ (hot-mix asphalt)	Stabilized-soil base & subbase + concrete slabs	Crushed-stone base & subbase + concrete slabs	Crushed-stone base & subbase + concrete pavers	
4. Presence of wildlife crossings	No crossing points	Barriers/culverts adapted for wildlife	Creation of	(a) + (b) + dry wildlife underpass for	(a) + (b) + (c) + mixed	(a) + (b) + (c) + (d) + wildlife	(a) + (b) + (c) + (d) + (e) +	

		– small-animal underpasses (a)	micro-habitats in other crossing structures (b)	medium and large animals (c)	underpasses for medium and large animals (d)	overpass – canopy bridges (e)	vegetated wildlife viaduct
5. Highway access control	No access control	Speed control (a)	(a) + weight control (b)	(a) + (b) + cargo-type control (c)	(a) + (b) + (c) + traffic time-window control (d)	(a) + (b) + (c) + (d) + noise-level control (e)	(a) + (b) + (c) + (d) + (e) + pollutant-emission control (f)
6. Right-of-way encroachment control	No occupation/encroachment control	Control by road agency (a)	(a) + control by supervising contractor (b)	(a) + (b) + control by municipality (c)	(a) + (b) + (c) + control by environmental agency (d)	(a) + (b) + (c) + (d) + control by military/security agency (e)	(a) + (b) + (c) + (d) + (e) + control by the third sector (NGOs/OSCIPIs) (f)
7. Presence of protective fencing (%)	No fencing	Fencing along 15% of the highway	Fencing along 35% of the highway	Fencing along 50% of the highway	Fencing along 65% of the highway	Fencing along 85% of the highway	Fencing along 100% of the highway
8. Presence of an environmental enforcement checkpoint	No enforcement checkpoint	1 checkpoint per 1,000 km	1 checkpoint per 750 km	1 checkpoint per 500 km	1 checkpoint per 250 km	1 checkpoint per 100 km	1 checkpoint per 50 km
9. Presence of a wildfire response unit	No wildfire response unit	1 unit per 500 km	1 unit per 200 km	1 unit per 100 km	1 unit per 50 km	1 unit per 25 km	1 unit per 10 km
10. Educational and guidance signage	No signage	Horizontal signage/markings (a)	(a) + regulatory and warning vertical signage (b)	(a) + (b) + directional/informational vertical signage (c)	(a) + (b) + (c) + auxiliary services signage (d)	(a) + (b) + (c) + (d) + educational signage (e)	(a) + (b) + (c) + (d) + (e) + tourism landmarks & gateway portals signage (f)

1	Hotspots > 50.0	20 Hotspots ≤ 50.0	1 5.0 < Hotspots ≤ 20.0	10.0 < Hotspots ≤ 15.0	5 Hotspots ≤ 10.0	1 Hotspots ≤ 5.0	0 Hotspots ≤ 1.0
1	Wage < 1.0 minimum wage (MW)	1. 0 MW ≤ Wage < 1.5 MW	1 .5 MW ≤ Wage < 2.0 MW	2.0 MW ≤ Wage < 2.5 MW	2 .5 MW ≤ Wage < 3.0 MW	3 .0 MW ≤ Wage < 4.0 MW	W age ≥ 4.0 minimum wages (MW)
1	D ≤ 5 km	5 km < D ≤ 20 km	2 0 km < D ≤ 40 km	40 km < D ≤ 60 km	6 0 km < D ≤ 80 km	8 0 km < D ≤ 100 km	D > 100 km
1	% of population ≤ 10.0	10 .0 < % ≤ 25.0	2 5.0 < % ≤ 40.0	40.0 < % ≤ 60.0	6 0.0 < % ≤ 75.0	7 5.0 < % ≤ 90.0	% of population ≥ 90.0
1	% of population ≤ 10.0	10 .0 < % ≤ 25.0	2 5.0 < % ≤ 40.0	40.0 < % ≤ 60.0	6 0.0 < % ≤ 75.0	7 5.0 < % ≤ 90.0	% of population ≥ 90.0
1	ISF ≤ 1.5	1. 5 < ISF ≤ 3.0	3 .0 < ISF ≤ 4.5	4.5 < ISF ≤ 5.5	5 .5 < ISF ≤ 7.0	7 .0 < ISF ≤ 8.5	I SF > 8.5
1	IDE B ≤ 1.5	1. 5 < IDEB ≤ 3.0	3 .0 < IDEB ≤ 4.5	4.5 < IDEB ≤ 5.5	5 .5 < IDEB ≤ 7.0	7 .0 < IDEB ≤ 8.5	I DEB > 8.5
1	IM > 32.5	27 .5 < IM ≤ 32.5	2 2.5 < IM ≤ 27.5	17.5 < IM ≤ 22.5	1 2.5 < IM ≤ 17.5	7 .5 < IM ≤ 12.5	I M ≤ 7.5

live births)							
1 9. Life expectancy at birth (years)	LE ≤ 60.0	60 $.0 < LE \leq 64.0$	6 $4.0 < LE \leq 68.0$	68.0 < LE ≤ 72.0	7 $2.0 < LE \leq 76.0$	7 $6.0 < LE \leq 80.0$	L E > 80.0
2 10. Homicide rate (per 100,000 inhabitants)	HR > 45	35 $< HR \leq 45$	2 $5 < HR \leq 35$	15 < HR ≤ 25	1 $0 < HR \leq 15$	5 $< HR \leq 10$	H R ≤ 5
2 11. Sustainable Cities Development Index (IDSC)	IDS C ≤ 35	35 $< IDSC \leq 45$	4 $5 < IDSC \leq 55$	55 < IDSC ≤ 65	6 $5 < IDSC \leq 75$	7 $5 < IDSC \leq 85$	I DSC > 85
2 12. Greenhouse gas emissions (tCO _{2e} per capita)	GH G > 50	40 $< GHG \leq 50$	3 $0 < GHG \leq 40$	20 < GHG ≤ 30	1 $0 < GHG \leq 20$	5 $< GHG \leq 10$	G HG ≤ 5
2 13. GDP per capita / 1,000 (BRL)	GDP pc ≤ 15	15 $< GDPpc \leq 25$	2 $5 < GDPpc \leq 35$	35 < GDPpc ≤ 45	4 $5 < GDPpc \leq 55$	5 $5 < GDPpc \leq 65$	G DPpc > 65
2 14. Employed population (%)	Emp l. ≤ 5	5 $< Empl. \leq 10$	1 $0 < Empl. \leq 15$	15 < Empl. ≤ 25	2 $5 < Empl. \leq 35$	3 $5 < Empl. \leq 40$	E mpl. > 40
2 15. Mobile phone access density (subscriptions per 100 inhabitants)	MP D ≤ 10	10 $< MPD \leq 25$	2 $5 < MPD \leq 40$	40 < MPD ≤ 60	6 $0 < MPD \leq 80$	8 $0 < MPD \leq 100$	M PD > 100

Note: Thresholds were calibrated for the present BR-364 application by combining technical-reference values, ordinal provision scales, and empirical-policy bands derived from public datasets. They are intended to support transparent corridor-scale diagnosis and may require context-sensitive recalibration in future applications.

After standardization and threshold definition, the indicator set was empirically applied to the BR-364/AC corridor between Manoel Urbano and Feijó. Table S3 reports the full operational application of the 25 indicators, including observed values, standardized scores, and corridor-level diagnostic inputs. This table constitutes the main empirical backbone of the present supplementary documentation because it makes explicit how the conceptual and classificatory logic of ISRAM was translated into the corridor diagnosis reported in the main manuscript.

Table S3

Empirical application of the 25 ISRAM indicators to the BR-364/AC corridor (Manoel Urbano–Feijó): observed values, standardized scores, and corridor-level diagnostic inputs.

Indicators (unit)	BR-364/AC - Corridor-wide assessment (Manoel Urbano–Feijó)	Score	Source (2020)
1. Highway platform width (m)	25 m < L	0	DNIT / Field (2020)
2. Right-of-way width (m)	$L \geq 100$ m	0	DNIT / Field (2020)
3. Pavement sustainability / service life	Stabilized-soil base & subbase + TSD (surface treatment)	150	DNIT / Field (2020)
4. Presence of wildlife crossings	Bridges/culverts adapted for wildlife – small-animal underpasses (a)	150	DNIT / Field (2020)
5. Highway access control	No access control	0	DNIT / Field (2020)
6. Right-of-way encroachment control	Control by road agency (a)	150	DNIT / Field (2020)
7. Presence of protective fencing (%)	No fencing	0	DNIT / Field (2020)
8. Presence of an environmental enforcement checkpoint	1 checkpoint per 250 km	700	Acre (2020)
9. Presence of a wildfire response unit	1 unit per 200 km	250	Acre (2020)

10. Educational and guidance signage	(a) + regulatory and warning vertical signage (b)		DNIT / Field (2020)
	Manoel Urbano	Feijó	
Classification (Score)			
11. Fire hotspots during the critical (driest) month	230 (0)	904 (0)	Acre (2020)
12. Average monthly wage of formally employed workers	2.1 (450)	1.7 (250)	IBGE (2020)
13. Distance from the project corridor to Indigenous Land (km)	40km < D ≤ 60km (450)	5km ≥ D (0)	FUNAI / Field (2020)
14. Access to water supply services	69.77 % (700)	17.96% (150)	IAS (2020)
15. Access to solid waste collection services	66.13 % (700)	51.33% (450)	IAS (2020)
16. Final Synthetic Indicator (ISF) – Primary Health Care	6.84 (700)	4.01 (250)	Brazil (2020)
17. Basic Education Development Index (IDEB) – early grades	4.55 (450)	5.05 (450)	IBGE (2020)
18. Infant mortality (deaths per 1,000 live births)	7.14 (1,000)	31.69 (150)	IBGE (2020)
19. Life expectancy at birth (years)	75.1 (700)	75.1 (700)	FIEAC (2020)
20. Homicide rate (per 100,000 inhabitants)	31.72 (250)	23.00 (450)	IPEA (2020)
21. Sustainable Cities Development Index (IDSC)	38.33 (150)	33.84 (0)	ICS (2020)
22. Greenhouse gas emissions (tCO _{2e} per capita)	166.31 (0)	151.40 (0)	SEEG (2020)
23. GDP per capita / 1,000 (BRL)	14.34 (0)	11.26 (0)	IBGE (2020)
24. Employed population (%)	5.3 (150)	5.9 (150)	IBGE (2020)
25. Mobile phone access density (subscriptions per 100 inhabitants)	57.1 (450)	56.1 (450)	ANATEL (2020)

Note: For corridor-wide indicators, values were assigned to the BR-364/AC segment through triangulation of field observation, DNIT technical inspection records, and project-related documentation. Field observation was used to verify operational features directly observable along the corridor, including surfacing condition, platform and right-of-way characteristics, signage, access-control features, fencing, wildlife crossing structures, and visible occupation pressure near the road domain. Final classification did not rely on field observation alone, but on combined assessment of these complementary sources. For municipality-based indicators, values for Manoel Urbano and Feijó were first obtained from institutional datasets, individually classified, and then incorporated into the corridor-level assessment according to the operational rules of the present application. Scores are expressed on the 0–1,000 ISRAM scale.

Taken together, Figure S2 and Tables S1–S3 define the operational core of ISRAM in the present study: Figure S2 provides the interpretive classification logic; Table S1 documents the structure and metadata of the indicator set; Table S2 makes the scoring thresholds explicit; and Table S3 records the full empirical application to the BR-364 corridor. In methodological terms, this combination establishes procedural replicability and case-based diagnostic plausibility rather than 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.

Accordingly, Part II presents the formal mathematical specification of the index and the robustness analysis used to test whether the main empirical interpretation remains stable under alternative assumptions of weighting, threshold definition, and aggregation logic.

3 PART II SUPPLEMENTARY ROBUSTNESS AND SENSITIVITY ANALYSIS

3.1 Supplementary note S1. Mathematical formulation of the isram diagnostic framework

The Index of Sustainability of Amazonian Roads (ISRAM) is structured as a multidimensional composite diagnostic framework designed to synthesize the regulatory and socioecological condition of tropical highway corridors. The framework combines five analytical dimensions—Environmental, Social, Economic, Institutional, and Technological—each represented by a set of standardized indicators scored on a common scale ranging from 0 to 1,000. The purpose of this note is to make explicit the mathematical structure used to construct the index and to document the operational rules adopted in the empirical application to the BR-364 corridor between Manoel Urbano and Feijó. This formulation is presented to ensure transparency, auditability, procedural replicability, and analytical consistency.

3.2 S1.1 Indicator standardization

Each indicator was first converted into a standardized score ranging from 0 to 1,000 according to the classification matrix presented in Table S2. Let x_{ij} represent the standardized score of indicator j belonging to dimension i , where:

- $i \in \{E, T, E_c, S, I\}$
- E = Environmental dimension
- T = Technological dimension
- E_c = Economic dimension
- S = Social dimension
- I = Institutional dimension

The standardization process converts heterogeneous raw variables into a common interpretive scale while preserving their directionality and diagnostic meaning. Higher scores represent more favorable regulatory and socioecological conditions, whereas lower scores indicate greater corridor-scale fragility or incompatibility.

3.3 S1.2 Dimensional aggregation

For each analytical dimension, the dimensional score D_i is obtained as the arithmetic mean of the standardized scores of the indicators included in that dimension:

$$D_i = \frac{1}{n_i} \sum_{j=1}^{n_i} x_{ij} \quad (1)$$

where:

- D_i = score of dimension i
- n_i = number of indicators in dimension i
- x_{ij} = standardized score of indicator j

This procedure preserves the internal variability of each dimension while generating a comparable synthetic value for Environmental, Social, Economic, Institutional, and Technological performance.

3.4 S1.3 Overall ISRAM aggregation

The baseline ISRAM score is calculated as the arithmetic mean of the five dimensional scores:

$$\text{ISRAM} = \frac{1}{5}(D_E + D_T + D_{EC} + D_S + D_I) \quad (2)$$

where:

D_E = Environmental score;

D_T = Technological score;

D_{EC} = Economic score;

D_S = Social score;

D_I = Institutional score.

The resulting ISRAM value ranges from 0 to 1,000. Higher values indicate more favorable corridor-scale regulatory and socioecological conditions, while lower values indicate increasing structural fragility. In the empirical application presented in the main manuscript, the baseline specification yielded a final score of 260.5, corresponding to the Bad category and indicating low corridor-scale performance in the BR-364 segment between Manoel Urbano and Feijó. The dimensional results reported in the main manuscript were: Environmental = 75.0; Social = 490.0; Economic = 237.5; Institutional = 420.0; Technological = 80.0. This profile reveals a markedly asymmetric diagnostic configuration, with a concentrated technological–environmental fragility core.

3.5 S1.4 Interpretation of the mathematical structure

The arithmetic formulation adopted in the baseline model is consistent with the diagnostic purpose of ISRAM. It allows transparent interpretation of both dimensional

and overall scores and facilitates comparison across analytical domains without obscuring internal asymmetries. At the same time, because composite indicators may be sensitive to weighting assumptions, threshold calibration, and aggregation rules, additional robustness tests were conducted to assess whether the substantive interpretation of the corridor remains stable under plausible alternative specifications. In methodological terms, the present application should therefore be read as establishing procedural replicability and case-based diagnostic plausibility, rather than 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.

The robustness of the ISRAM diagnosis was evaluated through a structured sensitivity analysis. The next note presents the rationale, tested scenarios, and resulting score variations for the BR-364 corridor under alternative methodological assumptions.

3.6 Supplementary note S2. robustness and sensitivity analysis: specifications, rationale, and calculation record

Composite indicators may be sensitive to methodological choices such as weighting schemes, classification thresholds, and aggregation rules. Sensitivity analysis is a standard procedure in composite indicator construction (Saisana et al., 2005; OECD/JRC, 2008). To evaluate the robustness of the Index of Sustainability of Amazonian Roads (ISRAM), a sensitivity analysis was conducted to test how alternative methodological specifications affect the resulting scores and the interpretation of corridor fragility.

The analysis focuses on three potential sources of methodological variability: (i) the weighting structure assigned to analytical dimensions, (ii) the classification thresholds used to convert indicator values into standardized scores, and (iii) the aggregation rule used to combine dimensional scores into the final value. The baseline specification corresponds to the operational configuration adopted in the main analysis, in which all five analytical dimensions receive equal weights, indicator thresholds follow the classification matrix presented in Table S2, and aggregation is performed using arithmetic means at both the dimensional and overall levels.

The purpose of the sensitivity analysis is not to replace the baseline specification, but to determine whether the empirical diagnosis obtained for the BR-364 corridor remains substantively stable under plausible alternative assumptions. In this sense, the robustness tests function as an additional verification step, strengthening the reliability and interpretability of the ISRAM results as a diagnostic tool for corridor-scale regulatory and socioecological assessment.

3.7 S2.1 Purpose of the sensitivity analysis

The sensitivity analysis evaluates whether the overall diagnostic interpretation of the BR-364 corridor depends excessively on specific modeling choices. In composite indices, different assumptions regarding weighting, threshold calibration, or aggregation may produce variations in the final score even when the empirical data remain unchanged. For this reason, robustness testing is particularly important when the objective is to identify structural fragilities rather than to produce a single deterministic value.

In the present case, the sensitivity analysis serves two related purposes. First, it tests whether the overall performance class and the main dimensional pattern remain stable under alternative specifications. Second, it evaluates whether the technological–environmental fragility core identified in the baseline model persists when the index is recalculated under different analytical assumptions. If the substantive interpretation remains stable, confidence in the diagnostic usefulness of ISRAM is strengthened.

3.8 S2.2 Alternative specifications tested

Three alternative scenarios were tested in addition to the baseline model.

Scenario 1 applies an alternative weighting scheme with greater emphasis on the Environmental and Technological dimensions, on the assumption that ecological compatibility and infrastructural adequacy are particularly decisive in Amazonian road corridors. The adopted weights were: Environmental = 0.30; Technological = 0.30; Economic = 0.10; Social = 0.15; Institutional = 0.15.

Scenario 2 introduces a modest threshold shift in the global classification system, testing whether the corridor's qualitative interpretation changes under moderate

adjustment of class boundaries. In practical terms, this scenario evaluates whether the baseline diagnosis remains stable if the lower bound of the Bad category is shifted upward.

Scenario 3 replaces arithmetic aggregation at the overall index level with the geometric mean. This specification reduces compensatory effects across dimensions and makes the final score more sensitive to very low performance in one or more analytical domains.

These scenarios were selected because they represent plausible methodological alternatives commonly discussed in the literature on index construction and diagnostic robustness. Together, they allow assessment of whether the baseline interpretation is an artifact of a single modeling choice or a stable expression of corridor-scale fragility.

3.9 S2.3 Robustness results

The robustness results are summarized in Table S4. Across all tested scenarios, the main empirical interpretation remained substantively stable. Under Scenario 1, the final score declined to 206.75, but the corridor remained in the Bad class. Under Scenario 2, the final score remained 260.50, and the qualitative classification did not change. Under Scenario 3, the final score declined to 196.54, producing a shift to the Very Bad class, yet the same technological–environmental fragility core was preserved. This pattern indicates that the substantive diagnosis is not dependent on a single arbitrary methodological assumption.

Table S4

Robustness and sensitivity analysis results for the ISRAM application to the Manoel Urbano–Feijó segment.

Scenario	Scenario	Specific	Final ISRAM score	Finance class	Performance	Technological–Environmental fragility preserved?	Interpretive core implication
Baseline	Baseline	Equal weighting across the five dimensions; arithmetic aggregation; original classification thresholds	.50	260	Bad	Yes	Reference specification
Scenario 1	Scenario 1	Alternative weighting scheme with greater emphasis on Technological and Environmental dimensions (Tech = 0.30; Env = 0.30; Econ = 0.10; Social = 0.15; Institutional = 0.15)	.75	206	Bad	Yes	More conservative score; qualitative diagnosis unchanged
Scenario 2	Scenario 2	Modest threshold shift in the global classification matrix (e.g., <i>Bad</i> starts at 225 instead of 200)	.50	260	Bad	Yes	Categorical interpretation remains stable under moderate threshold adjustment
Scenario 3	Scenario 3	Non-linear aggregation using the geometric mean across the five dimensional scores	.54	196	Very bad	Yes	The qualitative shift reflects the lower compensatory capacity of the geometric mean rather than a substantive change in the underlying empirical fragility pattern.

Note: *The table compares the baseline specification with three alternative scenarios involving modified dimensional weights, adjusted classification thresholds, and geometric aggregation. The objective is to verify whether the substantive diagnosis of low corridor-*

scale regulatory and socioecological performance, together with the preservation of a technological–environmental fragility core, remains stable under plausible methodological variation. The robustness tests are intended to support diagnostic confidence in the present case-based application and should not be interpreted as establishing universal calibration across all Amazonian corridors.

3.10 S2.4 Interpretation of robustness for replicability and transferability

Taken together, the robustness tests indicate that the ISRAM diagnosis is analytically stable under reasonable variation in weighting, thresholds, and aggregation logic. This does not imply that the framework is universally fixed or insensitive to context. Rather, it suggests that the BR-364 diagnosis is methodologically defensible and that the ISRAM architecture has transferability potential when applied with context-sensitive recalibration.

In that sense, ISRAM should be understood as a transferable diagnostic protocol with adaptable calibration, rather than as a universally fixed scoring template. Its value lies in preserving a stable analytical architecture—dimensions, scoring logic, and aggregation rules—while allowing selected empirical parameters to be revisited when the framework is transferred to other corridor settings.

3.11 S2.5 Closing statement for part II

Taken together, the methodological documentation and robustness tests presented in this Supplementary Material reinforce the transparency, analytical consistency, replicability, and conditional transferability of ISRAM as a multidimensional diagnostic framework. By combining explicit indicator metadata, standardized classification rules, formalized calculation procedures, detailed empirical application, and sensitivity testing under alternative specifications, the supplementary analysis supports the interpretation advanced in the main manuscript that the BR-364 corridor exhibits a structurally asymmetric pattern of corridor-scale fragility centered on technological and environmental constraints.

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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