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HYDROECOLOGICAL INTEGRITY OF AMAZONIAN STREAMS UNDER RIPARIAN DEGRADATION: AN INTEGRATIVE REVIEW WITH EMPHASIS ON PARÁ

INTEGRIDADE HIDROECOLÓGICA DE RIACHOS AMAZÔNICOS SOB DEGRADAÇÃO RIPÁRIA: REVISÃO INTEGRATIVA COM ÊNFASE NO PARÁ

Álisson Rangel Albuquerque, Alaison Felicio de Souza, Anderson Marcos Lima do Rosário, Vitória Karoline da Mata Mateus e Giulia Saboia Do Nascimento

ABSTRACT
Riparian vegetation regulates energy and matter inputs, sediment retention, bank stability, and water quality in Amazonian streams. This integrative review synthesized evidence made available between 2020 and 2025 on the effects of riparian degradation in lotic systems of the Brazilian Amazon, with emphasis on Pará. Searches were conducted in Scopus, Web of Science, SciELO, and the CAPES Journals Portal, followed by duplicate removal, title and abstract screening, full-text assessment, and qualitative synthesis. A total of 397 records were identified, of which 11 studies met the eligibility criteria. Studies conducted in Pará predominated; one paper reported only an eastern Amazon scope in the records consulted, and another included seven regions in Pará and one in Acre. Evidence converged on physicochemical changes in water, fine-sediment inputs, microhabitat simplification, and shifts in macrophytes, periphyton, zooplankton, aquatic insects, and benthic macroinvertebrates. In altered environments, higher local richness in some groups was associated with tolerant taxa, greater light availability, or nutrient enrichment rather than improved ecological integrity. The synthesis reinforces the need to protect and restore Permanent Preservation Areas, integrate complementary bioindicators, and expand standardized monitoring of Amazonian streams.
Keywords: Aquatic Bioindicators. Land Use. Fine Sediments. Biomonitoring. Forest Restoration.

RESUMO
A vegetação ripária regula a entrada de energia e matéria, a retenção de sedimentos, a estabilidade das margens e a qualidade da água em riachos amazônicos. Esta revisão integrativa sintetizou evidências disponibilizadas entre 2020 e 2025 sobre os efeitos da degradação ripária em sistemas lóticos da Amazônia brasileira, com ênfase no Pará. As buscas foram realizadas em Scopus, Web of Science e SciELO e no Portal de Periódicos CAPES, seguidas de remoção de duplicatas, triagem por título e resumo, leitura integral e síntese qualitativa. Foram identificados 397 registros, dos quais 11 estudos atenderam aos critérios de elegibilidade. Predominaram estudos realizados no Pará; em um trabalho a área foi reportada apenas como leste amazônico nos registros consultados, e outro incluiu, além de sete regiões paraenses, uma região no Acre. As evidências convergiram para alterações físico-químicas da água, aporte de sedimentos finos, simplificação de micro-hábitats e mudanças em macrófitas, perifíton, zooplâncton, insetos aquáticos e macroinvertebrados bentônicos. Em ambientes alterados, maior riqueza local de alguns grupos esteve associada a táxons tolerantes, maior luminosidade ou enriquecimento por nutrientes, sem representar melhoria da integridade ecológica. A síntese reforça a necessidade de proteger e restaurar Áreas de Preservação Permanente, integrar bioindicadores complementares e ampliar o monitoramento padronizado de riachos amazônicos.
Palavras-chave: Bioindicadores Aquáticos. Uso da Terra. Sedimentos Finos. Biomonitoramento. Restauração Florestal.

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1 INTRODUCTION

Low-order Amazonian streams connect hillslopes, soils, vegetation, and channels over short spatial distances. The proximity of the terrestrial matrix to the stream channel makes these systems particularly sensitive to changes in streamside vegetation, with consequences for light, temperature, particle retention, and water quality (Gu et al., 2025; Wang et al., 2024). At a broader scale, the Amazon is simultaneously exposed to deforestation, fire, fragmentation, mining, and agricultural expansion, pressures that can alter hydrological processes and biodiversity

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(Berenguer et al., 2024; Flores et al., 2024). This setting coincides with a global crisis affecting freshwater fauna, in which a substantial proportion of assessed species faces a high risk of extinction (Sayer et al., 2025).

Riparian vegetation functions as an interface between the terrestrial matrix and the stream channel. Its structure regulates incoming radiation, contributes to bank stability, intercepts particles, and influences nutrient dynamics and water quality (Gu et al., 2025; Wang et al., 2024). Disturbance of riparian buffers can degrade the physicochemical condition of stream water, while deforestation also modifies runoff through mechanisms associated with forest–climate interactions (Guimond et al., 2024; Ma et al., 2024). These processes are related but not equivalent: changes in runoff do not, by themselves, imply sedimentation or biological responses of the same magnitude in every stream.

In Pará, the conversion of streamside areas into mosaics of remnant forest, pasture, cropland, mining areas, roads, and urban development affects streams through mechanisms operating locally and at the landscape scale. Responses documented in regional studies include changes in dissolved oxygen, conductivity, nutrient availability, allochthonous resources, and the physical structure of habitats (Lima et al., 2022; Moy et al., 2022). Macrophytes, periphyton, zooplankton, Gerromorpha, Trichoptera, and benthic macroinvertebrates respond to different components of land use, environmental integrity, and water quality, supporting complementary assessments of stream ecological condition (Anacléto et al., 2024; Bomfim et al., 2026; Carmo et al., 2023; Jesus et al., 2026; Liberal et al., 2025; Trindade; Dunck, 2025).

Despite the growing body of evidence, regional studies remain dispersed across physicochemical variables, hydrosedimentological processes, habitat structure, and biological responses, making it difficult to interpret their findings collectively for biomonitoring and restoration. This limitation is particularly relevant to the spatial prioritization of Permanent Preservation Areas (APP), where management decisions must jointly consider soil, water, forest cover, and aquatic biodiversity (Alciaturi; Gil, 2025; Cruz et al., 2022). To address this gap, the present integrative review aimed to synthesize studies made available between 2020 and 2025 on the effects of riparian degradation on streams of the Brazilian Amazon, with emphasis on Pará, organizing the findings into physicochemical, hydrosedimentological, and biological domains while clarifying the geographic scope of the evidence.

2 MATERIALS AND METHODS

The review was conducted as an integrative synthesis of the literature. PRISMA 2020 was used to organize and transparently report the identification, screening, eligibility assessment, and inclusion of studies (Page et al., 2021). The guiding question was structured using the PECO framework: population, Amazonian streams; exposure, degradation or maintenance of riparian vegetation; comparators, different levels of environmental integrity; and outcomes, physicochemical, hydrosedimentological, and biological parameters.

The information sources were Scopus, Web of Science, SciELO, and the CAPES Journals Portal. The time frame encompassed studies made available from January 1, 2020, through December 31, 2025. Search terms in Portuguese and English were organized into four conceptual blocks: riparian vegetation; streams, igarapés, or lotic systems; the Amazon, Pará, or the Brazilian Amazon; and physicochemical, hydrosedimentological, or biological outcomes. Temporal eligibility was determined by the date of first electronic availability. Thus, articles published

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online in 2025 and subsequently assigned to regular 2026 issues remained in the corpus; the reference list uses the definitive bibliographic information from the versions of record.

Search string: ("riparian forest" OR "riparian vegetation" OR "riparian buffer*" OR "riparian zone*" OR "mata ciliar" OR "vegetação ripária" OR "floresta ripária") AND (stream* OR creek* OR "headwater stream*" OR river* OR igarapé* OR riacho* OR "sistema lótico" OR "ambiente lótico") AND (Amazon* OR Amazônia OR Pará OR "Eastern Amazon" OR "Brazilian Amazon") AND ("water quality" OR "dissolved oxygen" OR turbidity OR sediment* OR "suspended solids" OR hydrosedimentolog* OR "land use" OR "land-use change" OR "forest cover" OR periphyton OR macrophyte* OR zooplankton OR macroinvertebrate* OR "aquatic insect*" OR "habitat integrity" OR biomonitor*).

The syntax was adjusted to the operational requirements of each source without modifying the four conceptual blocks. Records were imported into Rayyan to organize screening, remove duplicates, and support title and abstract assessment (Ouzzani et al., 2016). Selection proceeded in four stages: record identification, duplicate removal, title and abstract screening, and full-text review of potentially eligible articles.

Eligible studies were empirical or applied investigations with original data made available within the specified time frame, reporting findings on Amazonian streams, igarapés, or other lotic systems, an explicit relationship to riparian vegetation, Permanent Preservation Areas, forest cover, land use, or environmental integrity, and at least one extractable physicochemical, hydrosedimentological, or biological outcome. The geographic scope encompassed the Brazilian Amazon, with emphasis on Pará, without requiring studies to be conducted exclusively within Pará when they included a regional component directly relevant to the review question.

Duplicate records; studies outside the time frame; articles not directly related to streams, igarapés, or lotic systems; studies outside the Amazon or unrelated to the regional scope; texts that did not assess riparian vegetation, land use, forest cover, or environmental integrity; documents without data extractable for the review question; exclusively marine, lentic, or laboratory studies without a connection to Amazonian streams; literature reviews and other secondary syntheses without original empirical data; theoretical essays; editorials; conference abstracts; book chapters; dissertations; theses; and reports not subjected to peer review were excluded.

Data extraction covered publication year, authors, study area, study design, environmental variable, biological group evaluated, main observed response, and implications for biomonitoring, conservation, or restoration. Municipal boundaries, watersheds, and protected areas were also recorded when explicitly identified in the publication or its bibliographic record. Heterogeneity among taxonomic groups, spatial scales, habitat metrics, and physicochemical variables precluded meta-analysis; accordingly, a qualitative synthesis was conducted along three axes: physicochemical water quality and sediments; habitat structure and restoration; and biological responses and bioindication. No formal risk-of-bias or methodological quality assessment tool was applied to the included studies, a point addressed in the limitations of the review.

3 RESULTS

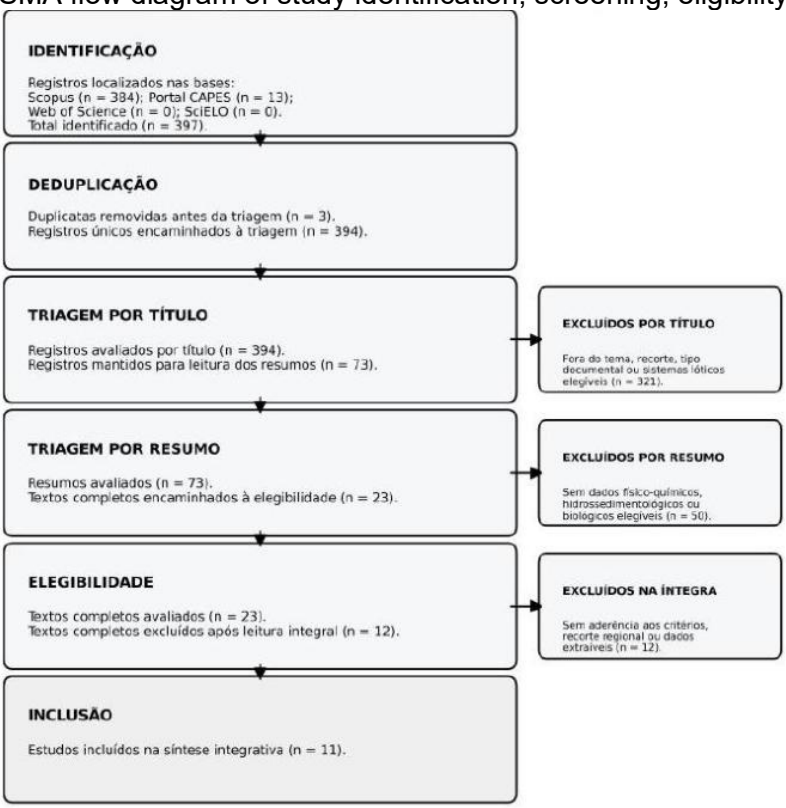
3.1 STUDY SELECTION

The searches identified 397 records: 384 in Scopus, 13 in the CAPES Journals Portal, none in Web of Science, and none in SciELO. After three duplicates were

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removed, 394 records underwent title screening. At this stage, 321 were excluded because they did not meet the topic, geographic scope, document-type, or lotic-system criteria. Of the 73 abstracts screened, 50 were excluded because they lacked eligible physicochemical, hydrosedimentological, or biological data. Twenty-three full texts were assessed, of which 12 were excluded after full-text review. Ultimately, 11 studies were included in the integrative synthesis.

Figure 1 - PRISMA flow diagram of study identification, screening, eligibility, and inclusion.



Source: Authors' own work, adapted from Page et al. (2021), using data from the present review.

3.2 SYNTHESIS OF INCLUDED STUDIES

The 11 selected studies were included under the 2020–2025 initial online-availability criterion; two were subsequently assigned to regular 2026 issues. For Bomfim et al. (2026), evidence of circulation in 2025 exists, but the initial online-publication date has not yet been independently confirmed in a primary publisher record. For nine studies, it was possible to explicitly verify that the study area was entirely within Pará. Carmo et al. (2023) reported 17 streams in the eastern Amazon, with no identifiable municipal delimitation in the records consulted. Bomfim et al. (2026) included 221 sites (162 streams and 59 ponds) distributed across seven regions of Pará and one region of Acre. Together, these studies provided evidence from Paragominas, Barcarena, Caxiuanã, Carajás, Tapajós, northeastern Pará, and other areas of the state, as well as the Acre component specified in Table 1.

The studies addressed macrophytes, periphyton, zooplankton, Gerromorpha, Ephemeroptera, Plecoptera, and Trichoptera, Trichoptera at different life stages, benthic macroinvertebrates, fine sediments, and priority areas for restoration of Permanent Preservation Areas. This breadth of topics made it possible to relate changes in the physical and chemical environment to biological responses, but called

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for caution because sampling designs, spatial scales, and outcomes were not directly comparable across studies.

Table 1 - Analytical characterization and geographic scope of the studies included in the integrative review.

No.	Study	Area or scale	Indicator or biota	Key variables	Main finding	Implication for hydroecological integrity
1	Carmo et al. (2023)	17 eastern Amazonian streams, with 150-m reaches. The publication identifies the eastern Amazon as the study region; municipal boundaries could not be verified in the records consulted.	Aquatic macrophytes	Riparian vegetation structure; canopy; understory; herbaceous vegetation	Riparian vegetation composition affected macrophyte assemblages. Greater herbaceous cover and low-growing vegetation favored species richness and composition.	Macrophytes reflect changes associated with canopy opening and riparian vegetation simplification; greater local richness alone must not be interpreted as greater integrity.
2	Lima et al. (2022)	30 first- to third-order streams in the Capim River watershed, Paragominas, Pará.	EPT functional feeding groups	Forest cover; exposed soil; water temperature; allochthonous resources	Shredders and gathering collectors were associated with streams with more riparian forest, fine roots, and live wood; filtering collectors predominated under greater exposed soil and higher temperatures.	Riparian loss reduces allochthonous resources and changes trophic functions, making EPT useful for functional biomonitoring.
3	Moy et al. (2022)	45 streams in the municipality of Paragominas, Pará.	Gerromorpha	Habitat Integrity Index; electrical conductivity; channel structure	Richness was related to environmental integrity, whereas community composition also responded to electrical conductivity.	Assessment of surface-dwelling insects should combine habitat structure with physicochemical water variables.
4	Cruz et al. (2022)	2,559 registered rural properties in Paragominas, Pará, with assessment of Permanent Preservation Areas and environmental liabilities.	Restoration of Permanent Preservation Areas	Land use; environmental liabilities; rivers; springs; forest remnants	Degraded Permanent Preservation Areas and environmental liabilities were mapped, identifying priority areas for restoration and connections between fragments.	The study provides complementary evidence for planning Permanent Preservation Areas at property and landscape scales, linking soil and water conservation with connectivity.
5	Felix et al. (2023)	20 soil and litter samples from riparian areas adjacent to two streams in Carajás	Hydrological processes and erosion	Leaf litter; runoff; percolation; turbidity; total suspended solids	Adding litter reduced runoff, sediment yield, turbidity, and	In riparian soils affected by fine sediment deposition, restoring

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		National Forest, Pará.			suspended solids in soil disturbed by fine-sediment deposition.	surface cover may reduce sediment transfer and improve water draining into streams.
6	Anacléto et al. (2024)	12 streams in Caxiuanã National Forest, Pará.	Larval and adult Trichoptera	Life-stage-specific environmental variables; assemblage structure	Larvae and adults differed in composition and responded to distinct ecological variables.	Trichoptera-based biomonitoring is more robust when larval and adult stages are interpreted as complementar y.
7	Palheta et al. (2025)	17 samples collected in the Pará River watershed on two occasions during the dry seasons of 2018 and 2019.	Periphytic algae	Physical integrity; total phosphorus; ammonia; aluminum; dissolved oxygen	Stream physical integrity was associated with total phosphorus, ammonia, and aluminum concentrations . Higher nutrient concentrations were associated with increased algal richness and divergence; the effect on evenness was unclear.	Greater richness does not necessarily indicate greater integrity; periphyton must be interpreted together with nutrients and physical habitat structure.
8	Trindade; Dunck (2025)	18 streams in the Tapajós watershed, along a reach of at least 100 km adjoining Amazonia National Park and its surroundings, southwestern Pará.	Periphytic algae	Land use; environmental integrity; beta diversity	Streams in preserved areas differed from agricultural settings and had greater environmental integrity and higher beta diversity; environmental integrity did not affect local species richness, density, or diversity.	Protected areas help maintain environmental heterogeneity and the structuring of aquatic communities.
9	Jesus et al. (2026)	37 first- to third-order streams in Abaetetuba, Acará, Barcarena, Ipixuna do Pará, Moju, Paragominas, and Tomé-Açu, Pará.	Aquatic macrophytes	Local and spatial factors; forest cover; pH; oxygen	Local environmental and spatial factors explained beta diversity and species replacement; richness differences were explained only by local environmental variables. Forest cover had no significant effect on macrophyte beta diversity.	Conservation should consider multiple streams and spatial variation among assemblages, not only local richness.

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10	Bomfim et al. (2026)	221 sites: 162 streams and 59 ponds, comprising seven regions of Pará (Altamira, Barcarena, Paragominas, Jamanxim National Forest, Saracá-Taquera National Forest/Oriximiná, Marajó Island, and Nascentes da Serra do Cachimbo Biological Reserve) and one region in Acre (Assis Brasil). This review considered regional relevance and distinguished lotic from lentic environments.	Zooplankton	Oxygen; temperature; pH; conductivity; forest cover; pasture	Of 190 recorded taxa (112 Rotifera, 57 Cladocera, and 21 Copepoda), pond-indicator species were identified, whereas none indicated streams as a system type. In streams, particular cladoceran species indicated forest or pasture cover, while other zooplankton taxa responded to water-quality conditions.	Species-specific indicators can complement assessments of land use and water quality in streams. The analysis also included ponds, and its findings must not be generalized to all sites as though they were lotic environments.
11	Liberal et al. (2025)	15 streams associated with the Itacaiúnas River watershed, Carajás Mountains, Pará.	Benthic macroinvertebrates	Anthropogenic impact; agriculture; body size and density	Agriculturally impacted areas showed reduced density across all size classes, indicating widespread abundance loss and simplification of trophic networks.	The density–body-size relationship extends taxonomic assessment and reveals losses in energy transfer and ecosystem resilience.

Source: Authors' own work, based on the 11 studies included in the review.
Note: Municipal boundaries were reported when explicitly stated in the article or in a verifiable bibliographic record; otherwise, the spatial scale reported by the authors was retained. Bomfim et al. (2026) included both lotic and lentic environments, which is specified to avoid unwarranted extrapolation to all 221 sites.

3.3 OBSERVED HYDROECOLOGICAL PATTERNS

The first body of evidence concerned physicochemical conditions. Streams affected by land-use changes and loss of riparian structure tended to show changes in temperature, pH, conductivity, and dissolved oxygen, as well as variations in nutrient availability. These effects were reported in studies of Gerromorpha, periphyton, zooplankton, and macrophytes, in which biological composition responded to local channel, water, and landscape conditions (Bomfim et al., 2026; Jesus et al., 2026; Moy et al., 2022; Palheta et al., 2025).

Hydrosedimentological evidence was less well represented in the corpus. The experimental study by Felix et al. (2023) showed that adding litter to riparian soil disturbed by fine-sediment deposition reduced runoff, sediment yield, turbidity, and suspended solids. This finding indicates that restoring surface cover and roughness can reduce particle transfer to the channel under conditions consistent with this

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mechanism, but does not justify generalization to every type of riparian environmental liability.

Biological responses varied among groups. Ephemeroptera, Plecoptera, and Trichoptera (EPT) indicated functional changes associated with the availability of allochthonous resources; Gerromorpha responded to habitat integrity and conductivity; periphyton and macrophytes showed greater richness in some disturbed environments, accompanied by changes in composition under increased light or nutrient availability; and benthic macroinvertebrates exhibited reduced density under agricultural pressure (Carmo et al., 2023; Liberal et al., 2025; Lima et al., 2022; Moy et al., 2022; Palheta et al., 2025). Together, richness, composition, functional attributes, and size structure describe distinct dimensions of hydroecological integrity.

4 DISCUSSION

The synthesis shows that riparian vegetation is not merely streamside cover, but an interface that regulates the movement of particles, nutrients, and energy between the soil and the stream channel (Gu et al., 2025; Wang et al., 2024). At a broader scale, freshwater biodiversity faces intense and increasing pressures, reinforcing the need to conserve local processes that maintain stream habitats (Sayer et al., 2025). In low-order systems, the close relationship between streambanks and channels means that seemingly localized changes can substantially modify light availability and inputs of terrestrial material.

Among the included Amazonian studies, removal or simplification of riparian vegetation was associated with canopy opening and changes in temperature, dissolved oxygen, conductivity, nutrients, and substrate structure, providing a combined signal of local- and landscape-scale degradation (Bomfim et al., 2026; Lima et al., 2022; Moy et al., 2022). Evidence outside the included corpus further indicates that land-use and land-cover changes can impair water quality and reorganize aquatic communities, while future environmental scenarios may alter water quality and riverine nutrient fluxes (Gay; Martin; Caldwell, 2025; Henderson; Hazlett; Drew, 2025; Lee et al., 2024; Liu et al., 2025). Although these findings converge, the study settings are not directly comparable; they nevertheless help place the mechanisms observed in Pará within the broader literature on land use and aquatic ecosystem functioning.

Biological responses highlight an important interpretive caution: species richness alone can mask degradation. In some altered streams, macrophytes and periphyton exhibited higher local richness under greater light availability or nutrient enrichment (Carmo et al., 2023; Palheta et al., 2025). Among benthic macroinvertebrates, the density–body size relationship revealed widespread reductions in abundance and simplification of trophic structure under anthropogenic pressure (Liberal et al., 2025). Accordingly, periphyton, macrophytes, zooplankton, Gerromorpha, EPT, Trichoptera, and benthic macroinvertebrates should be regarded as complementary indicators capable of capturing different components of stream structure and functioning (Anacléto et al., 2024; Bomfim et al., 2026; Lima et al., 2022; Trindade; Dunck, 2025). Multigroup approaches can also improve the spatial and temporal resolution of river biomonitoring (Perry et al., 2024).

The hydrosedimentological dimension warrants attention, although it was less well represented among the included studies. In disturbed riparian areas, the loss of surface cover can promote runoff and particle transport, with effects on turbidity and suspended solids. Felix et al. (2023) experimentally demonstrated that litter addition reduced these fluxes in soil affected by fine sediment deposition. Under a different climatic setting, changes in riparian buffer structure were also associated with shifts in

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water quality (Guimond et al., 2024), reinforcing the importance of diagnosing local mechanisms before selecting a restoration intervention.

For Pará, the evidence most directly applicable to land-use planning indicates the need to prioritize Permanent Preservation Areas (APP) with environmental liabilities, linking restoration, spring protection, connectivity, and soil and water conservation at property and landscape scales (Cruz et al., 2022). At the Amazonian scale, maintaining forest cover is also part of a broader set of measures needed to reduce the vulnerability of the forest system to critical transitions (Flores et al., 2024). Riparian buffers should be assessed by considering the spatial configuration of land use within buffer zones used to assess water quality (Alciaturi; Gil, 2025), together with measurable ecological outcomes. Studies on other continents show that the formal designation of protected areas does not, by itself, guarantee consistent benefits for river biodiversity (Sinclair et al., 2025).

The inferences of this review must be interpreted in light of the limitations of the included evidence. The 2020–2025 time frame favored recent findings but restricted the inclusion of longer historical series. The 11 studies differed in taxonomic groups, spatial scales, study designs, habitat metrics, and the physicochemical variables assessed. Geographic coverage was also uneven: nine studies had study areas explicitly verifiable as lying entirely within Pará; Carmo et al. (2023) described their study area as the eastern Amazon without identifying a municipality in the records consulted; and Bomfim et al. (2026) covered seven regions of Pará and one region of Acre. This heterogeneity prevented consistent comparisons of effect sizes and precluded meta-analysis. Moreover, no formal tool was used to assess risk of bias or the methodological quality of the studies, making it impossible to grade the strength of evidence according to the robustness of each design. Qualitative synthesis allows convergent findings to be identified, but does not support a single effect magnitude or undifferentiated generalizations to all watersheds in Pará or the Brazilian Amazon.

5 FINAL CONSIDERATIONS

The 11 studies associate riparian degradation with changes in water quality, sediment dynamics, habitat structure, and aquatic assemblages. Higher local richness under greater light or nutrient availability does not necessarily indicate improved hydroecological integrity.

The findings support riparian protection and restoration in Pará, with recovery assessed through complementary habitat, water-quality, and biological indicators rather than vegetation cover alone.

Interpretation is limited by the 2020–2025 time frame, methodological and taxonomic heterogeneity, uneven spatial coverage, and the absence of meta-analysis and formal risk-of-bias assessment. Nine studies were verifiably restricted to Pará; one covered the eastern Amazon without a confirmed municipal delimitation, and another included sites in Acre.

Future studies should use comparable indicators, broader spatial coverage, seasonal and long-term monitoring, and before-and-after restoration assessments to distinguish land-use effects from natural variability.

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