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Legal Compliance Does Not Ensure Riparian Integrity: Field Evidence from Permanent Preservation Areas in the Brazilian Cerrado

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Abstract

Protected riparian zones perform essential functions for hydrological stability, sediment retention, biodiversity conservation, and the maintenance of ecosystem services in agricultural landscapes. In Brazil, Permanent Preservation Areas constitute the main legal instrument for protecting these zones, but gaps remain regarding the correspondence between normative compliance and effective ecological integrity. This study assessed the condition of riparian zones in the upper course of the Claro River, in the Brazilian Cerrado, combining geoprocessing, satellite imagery, and field validation at 15 sampling points. The regular channel, the legally required width, the effectively preserved strip on each margin, and the main drivers of anthropogenic pressure were measured. The results indicated a predominance of non-compliance: 66.7% of the points were classified as non-compliant, 20% as partially compliant, and only 13.3% as compliant. The most critical situations occurred in reaches subject to wider legal buffers, confluences, and crossings, especially where native vegetation had been replaced by pastures, agriculture, and road infrastructure. Asymmetry between margins also revealed functional loss even when one of the channel margins remained preserved. The study concludes that the legal delimitation of riparian buffers, although necessary, is insufficient to ensure their ecological functionality without inspection, ecological restoration, and integrated territorial management.

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Keywords: riparian zones; Permanent Preservation Areas; environmental compliance; ecological functionality; Brazilian Cerrado; geoprocessing.

1 Introduction

Riparian zones are dynamic ecological interfaces between terrestrial and aquatic environments, performing central functions for watershed stability, landscape connectivity, and the maintenance of biogeochemical processes. In agricultural landscapes, these zones operate as multifunctional environmental protection structures by contributing to sediment and nutrient retention, bank stabilization, microclimatic moderation, biodiversity conservation, and water quality improvement (Gregory et al. 1991; Naiman and Décamps 1997; Cole et al. 2020). In the Brazilian Cerrado, where the conversion of native vegetation to agricultural and livestock uses has produced high environmental fragmentation, the conservation of riparian zones assumes additional relevance, since many remnants of native vegetation persist precisely along watercourses and legally protected areas (Nóbrega et al. 2020).

The literature has shown that the maintenance and restoration of riparian vegetation reduce sediment production and transport, increase infiltration capacity, protect soil attributes, and reinforce the provision of water-related ecosystem services (Martins et al. 2021; Fachinelli and Pereira 2023). However, the effectiveness of these functions depends not only on the formal existence of a protected buffer, but also on its width, continuity, vegetation structure, lateral connectivity, and position within the land-use context at the watershed scale (Cole et al. 2020). Thus, the assessment of riparian zones in anthropized landscapes requires the integration of legal criteria, spatial evidence, and field observations capable of capturing functional losses that are not fully revealed by isolated normative metrics.

In Brazil, riparian zones are legally protected largely through Permanent Preservation Areas (PPAs), established by Law No. 12,651/2012. The Forest Code establishes minimum protection widths along natural watercourses, defined according to the width of the regular channel, with the purpose of preserving water resources, geological stability, biodiversity, gene flow, soil, and the well-being of human populations (Brazil 2012). This normative model gives PPAs a simultaneously spatial and functional nature: they are not merely metric strips of land-use restriction, but ecological protection instruments aimed at maintaining sensitive environmental processes (Valera et

al. 2019). Nevertheless, the implementation of the Forest Code remains marked by challenges of compliance, inspection, and compatibility between environmental conservation and agricultural production on private properties (Soares-Filho et al. 2014).

The tension between legal delimitation and ecological functionality becomes even more complex in local contexts. In Jataí, Goiás, Municipal Law No. 3,069/2010 establishes a more restrictive parameter for urban areas by requiring a 150 m buffer per margin in certain urban reaches. Subsequently, Law No. 14,285/2021 amended the federal legal regime applicable to PPAs in consolidated urban areas, expanding the role of municipal regulations in defining urban marginal strips (Brazil 2021). This framework reveals a central issue for environmental management: the existence of legal parameters, even when formally protective, does not by itself ensure the ecological integrity of riparian zones when there is vegetation suppression, lateral fragmentation, cattle access to the channel, agricultural use, and road interventions in sensitive areas.

From a methodological perspective, the delimitation of PPAs has often been carried out with the support of geographic information systems and remote sensing, which are indispensable tools for watershed-scale analyses (Nowatzki et al. 2010; Campagnolo et al. 2017). However, the identification of the regular channel, an essential parameter for the application of the law, may present uncertainties in reaches covered by vegetation, low-slope areas, silted channels, confluences, and points affected by infrastructure. In such cases, field validation is necessary to reduce interpretive ambiguities and to verify whether the legally required width corresponds to the effectively preserved and functional strip.

The upper Claro River basin, located in southwestern Goiás, constitutes a strategic area for this type of assessment. It is a region embedded in a consolidated agricultural and livestock matrix, with a history of agricultural frontier expansion, native vegetation suppression, livestock pressure on river margins, and interferences associated with bridges, roads, and crossings (ANA 2015; Silva et al. 2013). In this context, the PPAs along the upper course of the Claro River function as key elements for conserving riparian connectivity, controlling erosive processes, and protecting water-related ecosystem services in an intensively used landscape.

This study evaluates the relationship between legal compliance and riparian integrity in the PPAs of the upper course of the Claro River, combining geoprocessing, satellite imagery, and field validation. The guiding question is: to what extent do the effectively preserved riparian strips correspond to the applicable legal requirements and

maintain minimum conditions of ecological functionality? The study is based on the hypothesis that reaches subject to wider legal buffers, confluence areas, and crossing points are more likely to present non-compliance and functional loss due to the intensification of anthropogenic pressures and the difficulty of maintaining riparian continuity on both margins.

The general objective is to evaluate the legal compliance and functional condition of PPAs in the upper course of the Claro River. Specifically, the study aims to: (i) measure the width of the regular channel in the field and classify each reach according to the corresponding legal category; (ii) quantify the effectively preserved width on each margin; (iii) identify anthropogenic pressures and structural interferences associated with the loss of riparian functionality; and (iv) propose a replicable diagnostic protocol for inspection, monitoring, and prioritization of restoration actions in agricultural watersheds. By demonstrating that formal compliance does not necessarily ensure ecological integrity, the study contributes to the international debate on the effectiveness of legal instruments for riparian protection in productive tropical landscapes.

2 Study Area

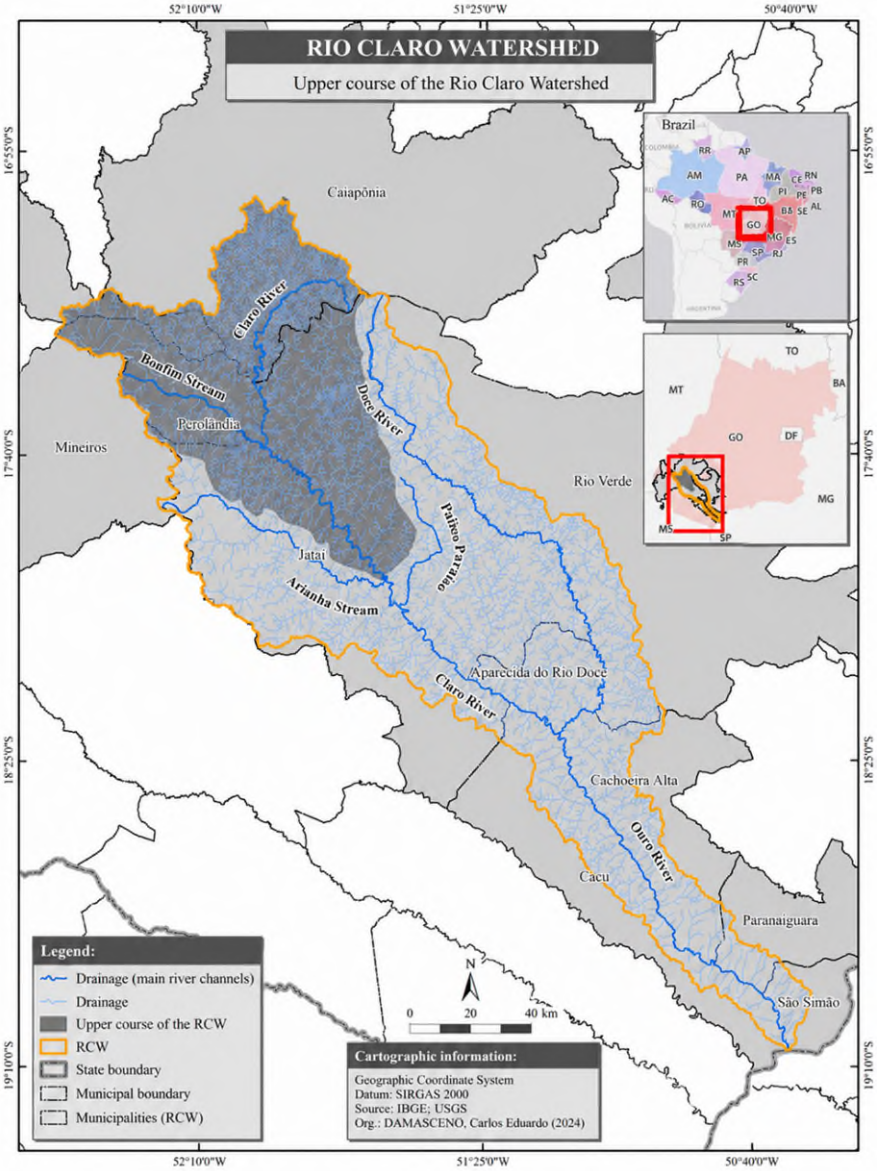
The study was carried out in the upper course of the Claro River, in the southwest of the state of Goiás, Brazil, in an area located within the Cerrado biome and the Paraná Hydrographic Region. The Claro River basin covers approximately 13,611 km² and is part of the Paranaíba River sub-basin, constituting a relevant hydrographic unit for the environmental and productive dynamics of south-central Goiás (ANA 2015; Santos and Martins 2018). The main channel extends for approximately 400 km and drains the municipalities of Jataí, Caiapônia, Perolândia, Aparecida do Rio Doce, Caçu, Cachoeira Alta, Paranaiguara, and São Simão (Prefeitura Municipal de Caçu 2022).

The analyzed area corresponds to the upper course of the Claro River, from its headwaters to the urban perimeter of Jataí. This reach was selected because it presents suitable conditions for assessing the effectiveness of Permanent Preservation Areas (PPAs), including the presence of springs and lower-order channels, an expressive altimetric gradient, morphological variation of the channel, confluences, road crossings, and different levels of agricultural and livestock pressure on the river margins.

The regional context is marked by the consolidation of agricultural and livestock activities in a Cerrado matrix, with the progressive replacement of native vegetation by

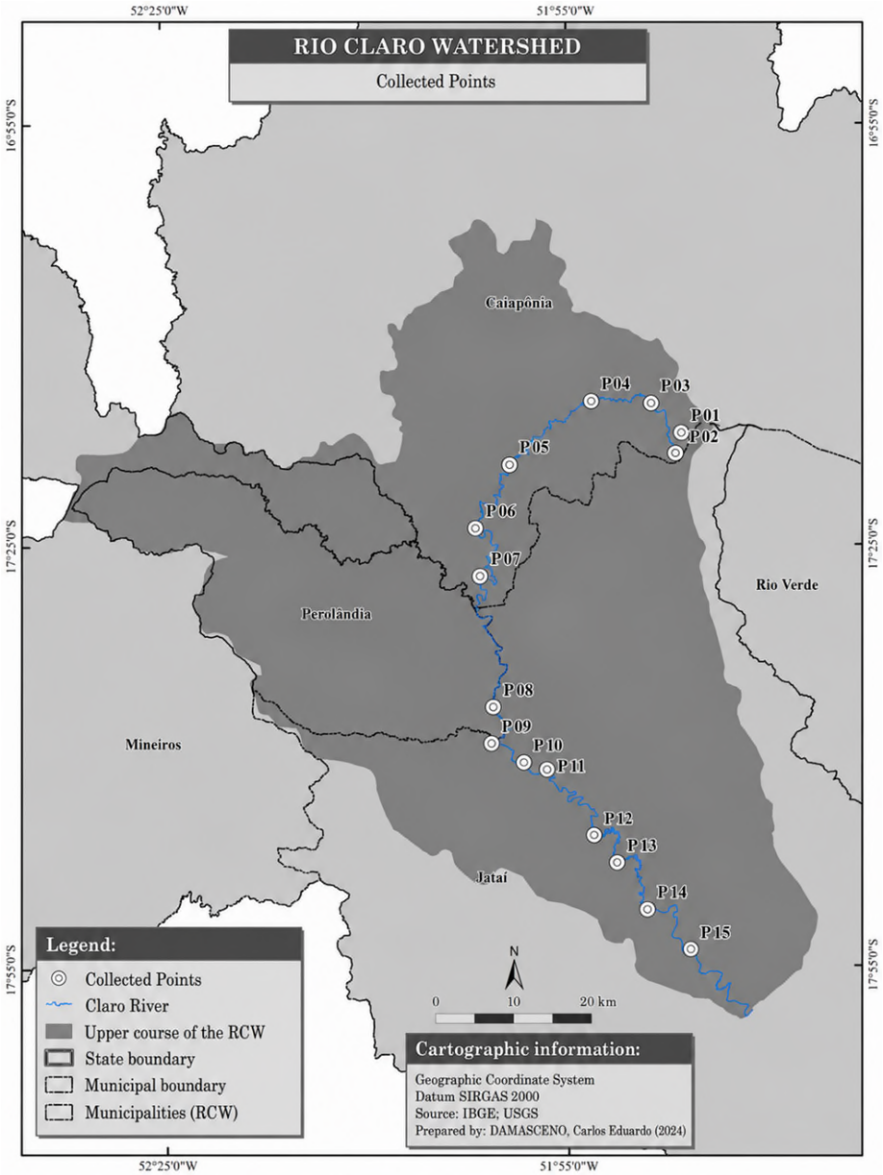
pastures, croplands, and linear infrastructures. This configuration makes the upper course of the Claro River an appropriate setting for examining the relationship between legal compliance, riparian vegetation conservation, and the ecological functionality of protected buffers. Fig. 1 shows the location of the study area, while Fig. 2 indicates the distribution of the sampled points along the evaluated reach.

Fig. 1 Location of the upper course of the Claro River, state of Goiás, Brazil



Source: Map prepared by Damasceno, Carlos Eduardo, 2024.

Fig. 2 Location of the analyzed points



Source: Map prepared by Damasceno, Carlos Eduardo, 2024.

3 Materials and Methods

3.1 Spatial data and preliminary mapping

The preliminary mapping was carried out based on thematic cartography, high-resolution satellite images, and hydrographic data available for the Claro River basin. This stage aimed to identify the course of the main channel, recognize representative reaches of the upper course, plan field access, and select candidate points for in situ validation.

Cartographic and hydrological data from MapBiomas, IBGE, and Google Earth were used. Spatial processing was conducted in QGIS and Google Earth Pro, adopting

the SIRGAS 2000 reference system. The images were used for preliminary channel delimitation, access identification, recognition of crossings, confluences, reaches with apparent riparian cover, and areas with adjacent agricultural and livestock use.

Based on this preliminary analysis, 34 candidate points were identified along the upper course of the Claro River. These points represented different morphological and anthropogenic conditions, including headwater areas, narrow channels, confluences, bridges, roads, meandering reaches, segments with continuous riparian vegetation, and areas showing signs of agricultural and livestock conversion.

3.2 Sampling design and field survey

The final sample consisted of 15 points selected from the 34 candidate points. The selection sought to balance three main criteria: (i) spatial representativeness along the longitudinal gradient of the upper course; (ii) morphological diversity of the river reaches; and (iii) presence of different anthropogenic pressures on the margins. The final number of points was defined as a compromise among territorial coverage, logistical feasibility, access safety, and the possibility of standardized recording of the observed conditions.

Field campaigns took place on October 5 and 6, 2024, during the dry season. The fieldwork was conducted by José Renato Nascimento Tiraboschi Filho under the supervision of Professor Pedro França Júnior, who also participated in the field survey. The choice of this period favored the identification of hydromorphological forms, bank slope limits, debris lines, recent bars, and other indicators used to delimit the regular channel. At each point, a representative section of the channel was selected, prioritizing reaches with clear morphological interpretation and avoiding, when possible, areas immediately affected by local distortions such as intense rapids, culverts, bridges, or artificial flow alterations.

At each section, the following were recorded: geographic coordinates, altitude, regular channel width, hydrological condition at the time of measurement, effectively preserved width on each margin, structure and continuity of riparian vegetation, presence of erosive processes, cattle access to the channel, agricultural use, exposed soil, roads, bridges, culverts, buildings, and other structural interferences. Standardized photographic records were also produced to document the condition of the margins, the measurement criteria, and the main drivers of anthropogenic pressure.

3.3 Delimitation and measurement of the regular channel

The regular channel was operationally defined as the channel occupied by flow under ordinary conditions, as indicated by observable morphological evidence in the field. This definition was applied uniformly to the 15 sampled points in order to reduce ambiguities in identifying the reference line used to calculate the legal PPA.

The in situ delimitation considered a convergent set of indicators: (i) break in slope on the bank; (ii) clear change in soil texture or vegetation cover; (iii) presence of debris lines, flow marks, or bioperiphyton; and (iv) top of recent bars, when applicable. In reaches where the edge of the regular channel was partially covered by vegetation, the criterion used for the reference line was recorded in the field and documented photographically.

The width of the regular channel was measured horizontally between the two edges of the channel using a manual tape measure, weighted tape measure, or laser distance meter, according to local access, depth, visibility, and safety conditions. The margins were identified as left and right in relation to the direction of flow. When hydrological or morphological conditions imposed relevant uncertainty, the measurement was qualified in the field record, indicating the condition observed at the time of data collection.

3.4 Legal framework and calculation of the protected buffer

After measuring the regular channel, each point was classified according to the corresponding legal category, based on the minimum PPA widths established by the Brazilian Forest Code, Law No. 12,651/2012. For natural perennial and intermittent watercourses, the legislation establishes marginal strips counted from the edge of the regular channel, with minimum widths varying according to the width of the watercourse (Brazil 2012).

In rural reaches, the following legal categories were applied: 30 m per margin for watercourses less than 10 m wide; 50 m for watercourses between 10 m and 50 m; 100 m for watercourses between 50 m and 200 m; 200 m for watercourses between 200 m and 600 m; and 500 m for watercourses wider than 600 m (Brazil 2012). In the urban reaches evaluated in the municipality of Jataí, the more restrictive municipal rule was considered, which establishes a 150 m buffer per margin in certain urban areas (Jataí 2010).

Law No. 14,285/2021, which amended the legal regime of PPAs in consolidated urban areas, was considered as a contextual element of the normative framework, especially due to the expansion of the role of local rules in defining urban marginal strips (Brazil 2021). Thus, for the purposes of calculating the legal PPA in this study, the municipal parameter in force in the analyzed urban reach was applied.

At points with ecological indications of vereda environments, such as the presence of buriti palms, hydromorphic soils, and waterlogging, the condition was descriptively recorded. However, in order to maintain comparability among the sampled points, the main compliance calculation considered only the watercourse-based classification. The possible incidence of specific vereda protection was treated as complementary ecological information.

Table 1 Legal criteria used to classify protected riparian buffers

Watercourse width, measured by the regular channel	Minimum PPA width per margin
Less than 10 m	30 m
From 10 m to 50 m	50 m
From 50 m to 200 m	100 m
From 200 m to 600 m	200 m
Greater than 600 m	500 m
Urban reach of Jataí, according to municipal regulation	150 m

Source: Brazil 2012; Jataí 2010.

3.5 Diagnostic protocol and classification criteria

At each sampling point, the effectively preserved width was measured separately on both margins of the river. The assessment was not limited to the metric presence of vegetation, but also considered the continuity of the riparian buffer, the structure of the vegetation cover, the occurrence of intense degradation, and the presence of uses or interferences incompatible with the ecological function of the PPA.

The final diagnosis was based on the limiting-margin rule. Under this criterion, the overall condition of the point was defined by the margin in the worst condition, since unilateral degradation may compromise lateral connectivity, geomorphological stability, and the hydrological function of the riparian buffer. This procedure prevents a preserved margin from concealing the functional loss of the opposite margin.

The points were classified into three analytical categories:

(i) Compliant: both margins presented a preserved width equal to or greater than 100% of the applicable legal minimum, with no incompatible use, irregular structure, or relevant degradation capable of compromising the ecological and hydrological function of the PPA.

(ii) Partially compliant: one margin presented a width equal to or greater than the legal minimum and the other maintained between 80% and 100% of the required width, without intense degradation; or both margins reached the minimum metric requirement but presented a localized impact capable of partially reducing the functionality of the riparian buffer.

(iii) Non-compliant: at least one margin presented a width lower than 80% of the legal minimum, or there was incompatible use, significant vegetation suppression, intense erosive process, recurrent cattle access to the channel, agricultural occupation, or structural interference capable of impairing the ecological and hydrological function of the PPA.

The analytical tolerance of 20% was not adopted as a legal flexibilization of the PPA nor as a normative interpretation of Law No. 12,651/2012. It is a methodological criterion used exclusively to grade intermediate conditions observed in the field, allowing the differentiation of severe non-compliance, partial compliance, and full preservation. The adoption of this criterion sought to incorporate uncertainties inherent to field measurement, local margin variations, and limitations inherent to the interpretation of riparian buffers in anthropized landscapes.

Finally, the data were organized in a comparative matrix containing: point identification, coordinates, altitude, regular channel width, applicable legal category, preserved width on the left margin, preserved width on the right margin, main pressures observed, and final diagnosis. This matrix allowed the comparison of compliance patterns among legal classes, the identification of lateral asymmetries, and the recognition of priority reaches for inspection, restoration, and management.

4 Results

4.1 General pattern of PPA compliance

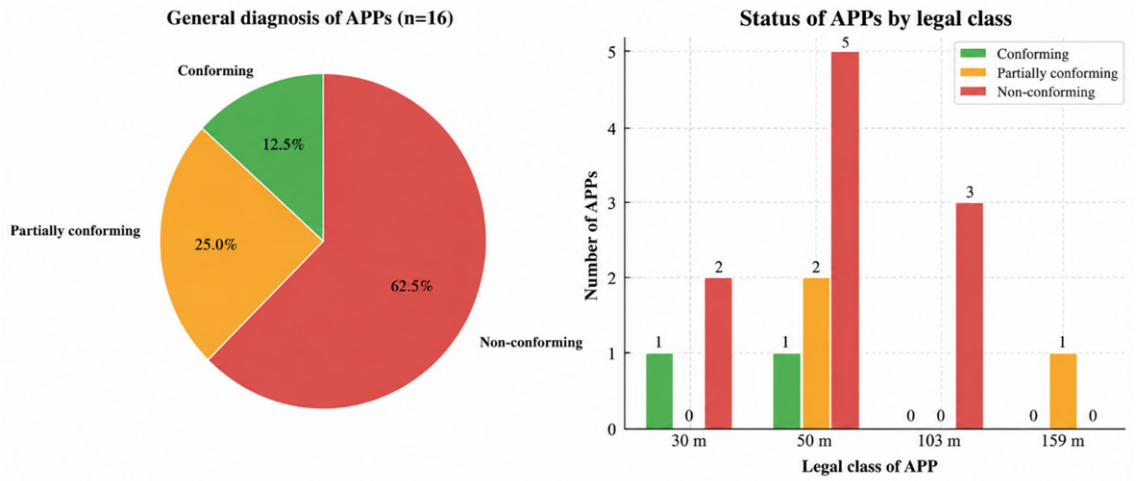
Fifteen points were evaluated along the upper course of the Claro River, with altitudes between 631 m and 853 m and regular channel widths ranging from approximately 2 m to 79 m. The legal classification resulted in four categories of protected marginal strips: 30 m per margin at three points, 50 m at eight points, 100 m at three points, and 150 m at one point located in the urban reach of Jataí.

The diagnosis indicated a predominance of legal and functional non-compliance in the riparian buffers. Of the 15 points evaluated, 10 were classified as non-compliant, corresponding to 66.7% of the sample. Another three points, equivalent to 20.0%, were classified as partially compliant, while only two points, or 13.3%, presented full

compliance. This pattern indicates that most of the analyzed reaches do not maintain an effectively preserved riparian width under conditions compatible with the applicable legal parameters and with the ecological functionality expected for PPAs.

The distribution of diagnoses also showed that non-compliance is not restricted to isolated points. Critical situations occurred both in headwater areas and in wider river reaches, especially where the required legal buffer is wider or where there is a concentration of pressures associated with agricultural and livestock use, asymmetry between margins, and crossing infrastructure.

Fig. 3 General diagnosis of PPAs in the upper course of the Claro River



Source: Research data.

4.2 Compliance by legal PPA category

The analysis by legal category revealed poorer performance in reaches subject to wider marginal buffers. All points classified in the 100 m PPA category were classified as non-compliant. In these reaches, the effectively preserved width on at least one of the margins was substantially below the legal minimum, indicating greater difficulty in maintaining riparian continuity in segments with greater regular channel width.

In the 50 m PPA category, greater variability was observed. Of the eight points classified in this category, five were classified as non-compliant, two as partially compliant, and only one as compliant. This category included both situations of severe degradation associated with agricultural and livestock use, exposed soil, and occupations within the protected buffer, as well as reaches with satisfactory preservation on one or both margins.

Among the three points subject to a 30 m PPA, two were classified as non-compliant and one as compliant. Although the metric requirement is smaller in this category, the presence of erosive processes, cattle trampling, and suppression of riparian vegetation compromised the protective function in part of the headwater reaches. At the urban point in Jataí, subject to a 150 m buffer per margin, the diagnosis was partial compliance, since both margins presented relevant vegetation cover but below the limit established by the applicable municipal regulation.

Table 2 Total observation data for the points

Point	Altitude	Regular channel width	Legal PPA category	Preserved left margin	Preserved right margin	Diagnosis
P1	853 m	≈ 2 m	30 m	≈ 7 m	≈ 7 m	Non-compliant
P2	842 m	≈ 5 m	30 m	> 30 m	> 30 m	Compliant
P3	766 m	≈ 11 m	50 m	≈ 16 m	≈ 14 m	Non-compliant
P4	744 m	≈ 7 m	30 m	≈ 8 m	≈ 16 m	Non-compliant
P5	732 m	≈ 13 m	50 m	> 50 m	> 50 m	Partially compliant
P6	714 m	≈ 16 m	50 m	≈ 9 m	≈ 48 m	Non-compliant
P7	703 m	≈ 18 m	50 m	≈ 8 m	> 50 m	Non-compliant
P8	672 m	≈ 64 m	100 m	> 100 m	≈ 36 m	Non-compliant
P9	662 m	≈ 30 m	50 m	≈ 26 m	> 50 m	Non-compliant
P10	660 m	≈ 79 m	100 m	≈ 26 m	≈ 19 m	Non-compliant
P11	654 m	≈ 30 m	50 m	≈ 28 m	≈ 43 m	Non-compliant
P12	646 m	≈ 34 m	50 m	> 50 m	> 50 m	Compliant
P13	639 m	≈ 38 m	50 m	≈ 39 m	> 50 m	Partially compliant
P14	633 m	≈ 70 m	100 m	≈ 82 m	≈ 64 m	Non-compliant
P15	631 m	≈ 43 m	150 m	≈ 126 m	≈ 118 m	Partially compliant

Source: Research data.

4.3 Asymmetry between margins and the effect of the limiting margin

Asymmetry between margins was observed at four points, corresponding to 26.7% of the sample. In these cases, one margin presented a preserved width equal to or greater than the legal minimum, or close to it, while the opposite margin maintained an expressive deficit of riparian vegetation. This condition was recorded at points 7, 8, 9, and 13.

The occurrence of asymmetry indicates that the assessment of riparian compliance cannot be limited to the presence of vegetation on only one margin. In functional terms, unilateral degradation reduces lateral connectivity, increases vulnerability to erosive processes, and compromises the PPA's capacity to protect the channel against sediments, nutrients, and land-use pressures. For this reason, the application of the limiting-margin rule made it possible to identify situations in which a preserved margin could mask the functional loss of the opposite margin.

The most expressive case occurred in reaches classified as 100 m PPAs. At point 8, for example, one margin presented a preserved strip greater than the legal minimum, while the opposite margin maintained approximately 36 m of vegetation, far below the required 100 m. A similar situation was observed in reaches classified as 50 m PPAs, in which a preserved margin coexisted with a strong reduction of vegetation on the opposite margin.

4.4 Consistency between geoprocessing and field measurements

The comparison between values estimated by geoprocessing and measurements carried out in the field indicated proximity between the results at most of the evaluated points. This correspondence suggests that the use of satellite images and geoprocessing tools constitutes a useful basis for screening, sampling planning, and preliminary delimitation of priority reaches.

However, the results also indicate that field validation is indispensable for the final diagnosis of PPA compliance. In reaches with dense vegetation, covered margins, silted channels, confluences, bridges, or local flow alterations, remote interpretation may not adequately capture the position of the regular channel, the effectively preserved width, or the localized impacts observed in situ. Thus, geoprocessing should be understood as a complementary, and not substitutive, stage of field assessment.

The combination of spatial analysis and direct measurement allowed the production of a more robust diagnosis of the riparian condition, especially because it incorporated information not detectable only by imagery, such as cattle trampling, soil compaction, bank erosion, presence of trails, understory degradation, and localized structural interferences.

Table 3 Comparison between regular channel width estimated by geoprocessing and measured in the field

Point	Regular channel width estimated by geoprocessing (m)	Regular channel width measured in the field (m)
P1	0	2
P2	5	5
P3	8.2	11
P4	7.4	7
P5	14.8	13
P6	16.12	16
P7	20.6	20
P8	68	64
P9	36.8	40
P10	72.8	72
P11	33.31	30

P12	44	34
P13	42	38
P14	69.63	70
P15	51.2	50

Source: Research data.

4.5 Field diagnosis of the sampled points

The individual analysis of the sampled points made it possible to identify relevant local variations in the condition of the PPAs, especially regarding the effectively preserved width, the continuity of riparian vegetation, and the presence of anthropogenic pressures. Although the general diagnosis reveals a predominance of non-compliance, the point-by-point assessment shows that the functional loss of riparian buffers results from different combinations of metric deficit, agricultural and livestock use, erosive processes, asymmetry between margins, and structural interferences.

Fig. 4 Area of P1: Narrow water thread, on-site measurement, and presence of gullies in the surroundings



Source: Photograph by the authors (2024).

At P1, located in a headwater area, the regular channel was approximately 2 m wide, with a legal PPA of 30 m per margin. The preserved strip was only approximately 7 m on each margin, in an environment with buriti palms, hydromorphic soils, cattle trampling, and erosive processes. The presence of *Mauritia flexuosa*[3] and waterlogged soil indicates a possible vereda configuration, which may imply specific legal protection in addition to the PPA associated with the watercourse. In this study, this condition was recorded as complementary ecological information, without changing the main criterion of comparison among the points. The point was classified as non-compliant, with severe loss of protective function.

[3] The paths are a typical savanna phytophysiognomy of humid soils, marked by the presence of buriti (Mauritia flexuosa), as well as herbs and subshrubs. They have a linear shape along narrow watercourses, forming swampy strips in shallow valleys, generally in the riparian zone of streams (Rosolen et al., 2014).

Fig. 5 Area of P2: Narrow water thread, on-site measurement, and presence of gullies in the surroundings



Source: Photograph by the authors (2024).

P2 presented a regular channel approximately 5 m wide and a legal PPA of 30 m per margin. Despite the presence of steep banks and gullies in the surroundings, both margins maintained riparian vegetation above the legal minimum, ensuring stability and lateral connectivity. The diagnosis was compliance.

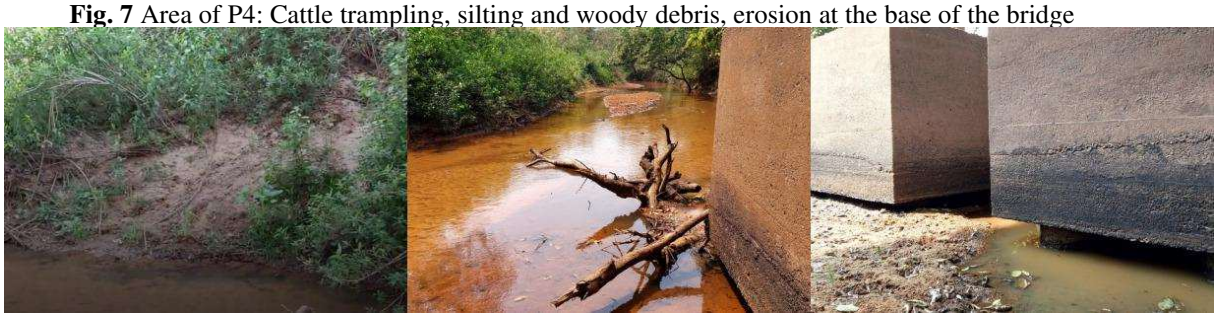
Fig. 6 Area of P3: River measurement, silting, cattle trampling, and bank erosion



Source: Photograph by the authors (2024).

At P3, the regular channel measured approximately 11 m, classifying the reach in the 50 m PPA category per margin. The preserved strips were approximately 16 m on the left margin and 14 m on the right margin, with signs of silting, cattle trampling, bank instability, and understory fragmentation. The point was classified as non-compliant.

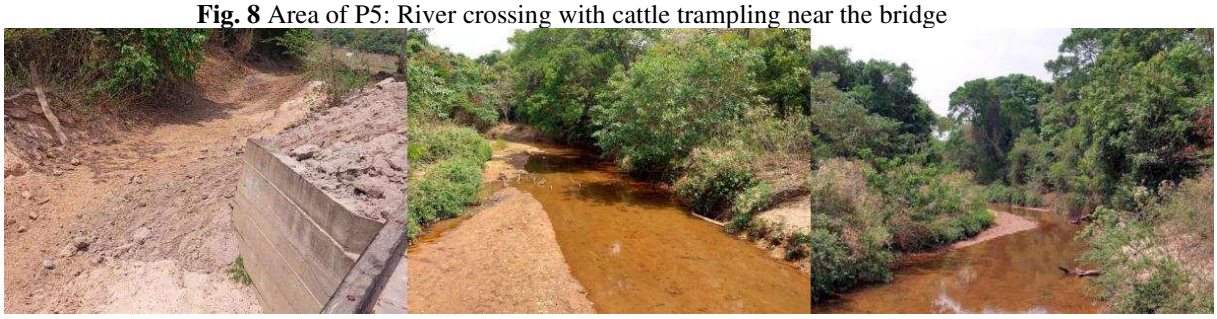
Fig. 7 Area of P4: Cattle trampling, silting and woody debris, erosion at the base of the bridge



Source: Photograph by the authors (2024).

P4, located next to the BR-158 crossing, presented a regular channel approximately 7 m wide and a legal PPA of 30 m per margin. The preserved margins, approximately 8 m and 16 m, were below the legal minimum. The presence of silting, accumulated woody debris, cattle trampling, and erosion at the base of the bridge indicated loss of hydrological and geomorphological functionality, resulting in a diagnosis of non-compliance.

Fig. 8 Area of P5: River crossing with cattle trampling near the bridge



Source: Photograph by the authors (2024).

At P5, the regular channel was approximately 13 m wide, with a legal PPA of 50 m per margin. Although both margins presented vegetation above the legal minimum, exposed soil, compaction, and cattle circulation near the rural bridge were observed. Localized degradation reduced the functionality of the protected strip, justifying the diagnosis of partial compliance.

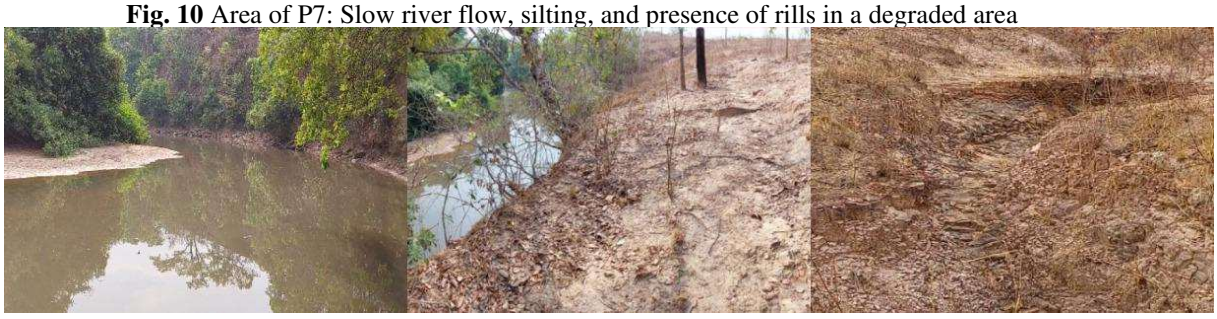
Fig. 9 Area of P6: Upstream and downstream sectors, and the state of PPA preservation



Source: Photograph by the authors (2024).

P6 presented a regular channel approximately 16 m wide and a legal PPA of 50 m per margin. The left margin maintained only approximately 9 m preserved, while the right margin reached approximately 48 m. The presence of a road, bridge, and building within the protected buffer aggravated functional loss, leading to a diagnosis of non-compliance.

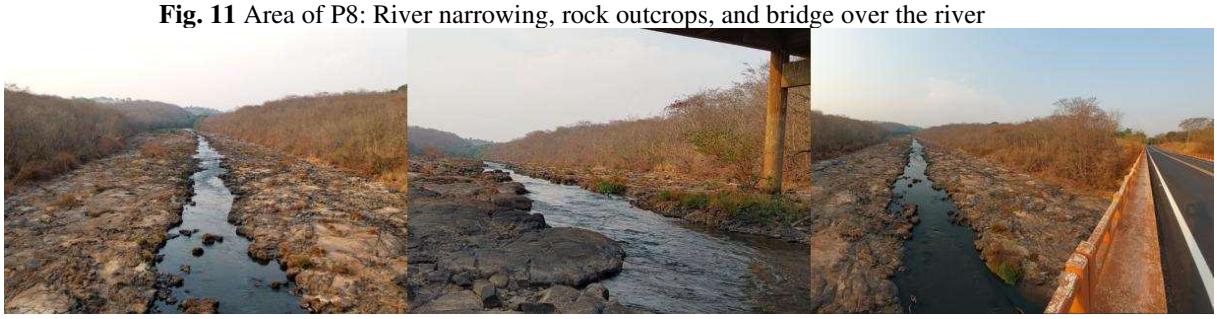
Fig. 10 Area of P7: Slow river flow, silting, and presence of rills in a degraded area



Source: Photograph by the authors (2024).

At P7, the regular channel measured approximately 18 m, with a legal PPA of 50 m per margin. The right margin presented vegetation above the legal minimum, but the left margin maintained only approximately 8 m preserved, with rills, exposed soil, and active erosion. The strong asymmetry between margins and the degradation of the limiting margin resulted in non-compliance.

Fig. 11 Area of P8: River narrowing, rock outcrops, and bridge over the river



Source: Photograph by the authors (2024).

P8 corresponds to a wider reach, with a regular channel approximately 64 m wide and a legal PPA of 100 m per margin. The left margin presented preservation above the legal minimum, while the right margin maintained only approximately 36 m of vegetation, with the presence of mechanized agriculture and sections of highly reduced vegetation. Lateral asymmetry and land-use conversion led to a diagnosis of non-compliance.

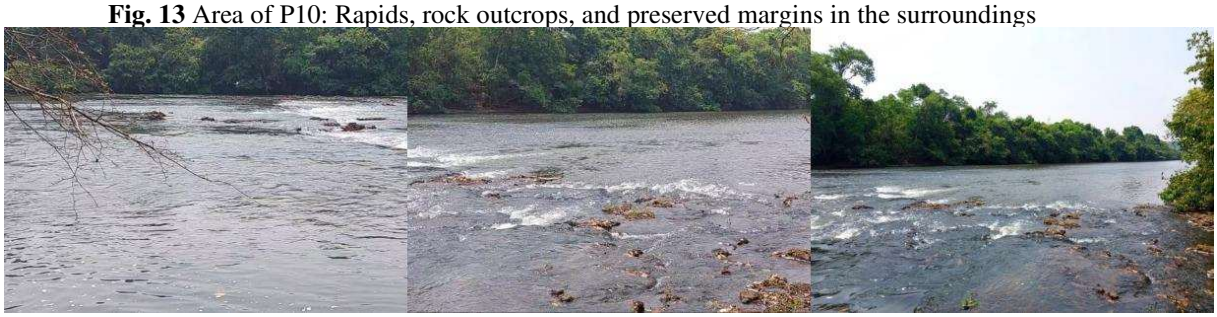
Fig. 12 Area of P9: Upstream and downstream sectors, and confluence with the Bonfim Stream



Source: Photograph by the authors (2024).

At P9, located in the confluence area with the Bonfim Stream, the regular channel was approximately 30 m wide, with a legal PPA of 50 m per margin. The right margin was preserved above the legal minimum, but the left margin maintained only approximately 26 m, with exposed soil, agricultural use, and anthropogenic interferences. Because it is a strategic area for hydrological and ecological connectivity, unilateral degradation compromised the functionality of the system, resulting in non-compliance.

Fig. 13 Area of P10: Rapids, rock outcrops, and preserved margins in the surroundings



Source: Photograph by the authors (2024).

P10 presented a regular channel approximately 79 m wide, being classified in the 100 m PPA category per margin. Both margins were far below the legal minimum, with approximately 26 m preserved on the left margin and 19 m on the right margin. The

presence of pastures, agricultural areas, and suppression of riparian vegetation indicated expressive loss of ecological function, justifying the diagnosis of non-compliance.

Fig. 14 Area of P11: Calm flow, well-preserved margins, and high banks



Source: Photograph by the authors (2024).

At P11, the regular channel measured approximately 30 m and the legal PPA was 50 m per margin. Despite the presence of reaches with arboreal cover and high banks, the margins presented only approximately 28 m and 43 m preserved, in addition to partial conversion of the PPA into agricultural area and the presence of infrastructure. The point was classified as non-compliant.

Fig. 15 Area of P12: Crossing for measurement, upstream and downstream sectors, with PPA in the background



Source: Photograph by the authors (2024).

P12 presented a regular channel approximately 34 m wide and a legal PPA of 50 m per margin. Both margins maintained continuous riparian vegetation above the legal minimum, with no record of recent agricultural or livestock use within the protected buffer. The diagnosis was compliance.

Fig. 16 Area of P13: Upstream and downstream sectors, sedimentation, and animal impacts on the margins

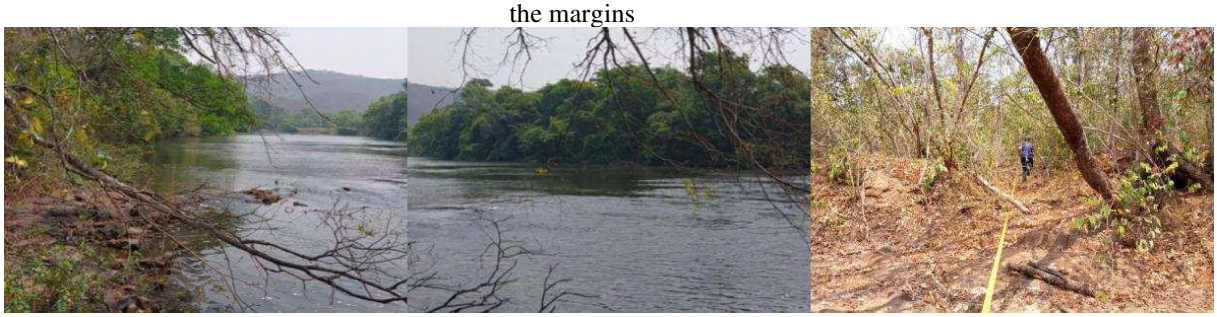


Source: Photograph by the authors (2024).

At P13, the regular channel was recorded as approximately 38 m, with a legal PPA of 50 m per margin. The right margin presented vegetation above the legal minimum, while the left margin maintained approximately 39 m preserved. The presence of

localized impacts resulting from animal access and localized erosion led to a diagnosis of partial compliance.

Fig. 17 Area of P14: Upstream sector with PPA in the background and measurement carried out on one of the margins



Source: Photograph by the authors (2024).

P14 presented a regular channel approximately 70 m wide, with a legal PPA of 100 m per margin. Neither margin fully reached the minimum required width, with approximately 82 m preserved on the left margin and 64 m on the right margin. The partial conversion of native vegetation into agricultural use reinforced the diagnosis of non-compliance.

Fig. 18 Area of P15: Bridge of the Jataí/GO ring road and wide river with preserved margins



Source: Photograph by the authors (2024).

P15, located in the urban reach of Jataí, was analyzed under the municipal parameter of 150 m per margin. Although it presents relevant vegetation cover outside the immediate zone of influence of the bridge, the preserved widths, approximately 126 m on the left margin and 118 m on the right margin, were below the applicable legal limit. The presence of localized impacts associated with the ring road justified the diagnosis of partial compliance.

In summary, the point-by-point analysis confirms that non-compliance in the PPAs of the upper course of the Claro River does not result from a single driver of degradation. The observed pattern results from the combination of insufficient preserved width, unilateral degradation, cattle access to the channel, agricultural use, erosive processes, and interferences associated with bridges, roads, and crossings. The compliant points demonstrate that the maintenance of continuous riparian vegetation is possible, but

they appear as exceptions within a matrix predominantly pressured by agricultural and livestock uses and infrastructure.

5 Discussion

5.1 Legal compliance and riparian integrity: a necessary but insufficient relationship

The results demonstrate that the existence of legally protected buffers does not, by itself, ensure the ecological integrity of riparian zones. Although Permanent Preservation Areas are conceived by the Brazilian Forest Code as instruments for protecting water resources, geological stability, biodiversity, soil, and human well-being, most points evaluated in the upper course of the Claro River presented deficits in preserved vegetation, incompatible uses, or functional degradation of the margins. This finding confirms the central hypothesis of the study: normative compliance must be analyzed not only as a legal measure of width, but also as a functional condition dependent on vegetation continuity, margin integrity, and the absence of anthropogenic pressures capable of compromising ecological processes.

The situation observed in the upper Claro River reinforces a relevant issue for environmental management in tropical agricultural landscapes: legal instruments for spatial protection are essential, but their effectiveness depends on concrete implementation in the territory. In the Brazilian case, the Forest Code establishes a robust normative architecture for the protection of riparian zones, but its application has historically been tensioned by agricultural expansion, the regularization of environmental liabilities, and the challenges of inspection on private properties (Soares-Filho et al. 2014; Valera et al. 2019). Thus, the results of this study should not be interpreted only as a local diagnosis of non-compliance, but as empirical evidence of a recurring gap between formal legal protection and real ecological effectiveness.

This distinction is especially important because riparian zones perform functions that go beyond the mere presence of vegetation in a metric buffer. They act as interfaces between terrestrial and aquatic systems, regulating flows of sediments, nutrients, organic matter, energy, and biodiversity (Gregory et al. 1991; Naiman and Décamps 1997). In agricultural landscapes, their function depends on width, vegetation structure, lateral and longitudinal connectivity, position in the watershed, and the intensity of adjacent land

uses (Cole et al. 2020). Therefore, a PPA may exist as a legal category but fail to operate as a functional riparian zone when vegetation is fragmented, when there is recurrent cattle access to the channel, or when the protected buffer is interrupted by agriculture, exposed soil, roads, and bridges.

5.2 Wider PPAs and greater territorial vulnerability

The greater non-compliance observed in reaches subject to 100 m and 150 m PPAs reveals a relevant pattern for environmental management. In normative terms, wider buffers are required precisely in reaches with greater watercourse width or in areas with a more restrictive local legal regime. However, in the upper Claro River, these reaches also coincided with segments more pressured by agricultural and livestock uses, crossings, infrastructure, and conversion of native vegetation. This indicates that increased legal requirements do not automatically translate into greater effective protection.

This result should be interpreted in light of the regional context of the Goiás Cerrado, marked by strong agricultural frontier expansion, replacement of native vegetation by pastures and croplands, and consolidation of productive systems in areas of high agricultural aptitude (Silva et al. 2013). The literature on the Forest Code already indicates that the implementation of PPAs depends on compatibility between conservation and production, especially on private properties and agricultural watersheds where land-use pressure is high (Soares-Filho et al. 2014; Valera et al. 2019). In the upper Claro River, this tension appears concretely: the wider the legally required buffer, the greater the tendency for difficulty in maintaining riparian continuity on both margins.

However, this pattern does not mean that wider legal buffers are inadequate. On the contrary, the literature shows that the restoration and conservation of riparian vegetation can reduce sediment production and transport, improve water quality, and strengthen the provision of ecosystem services in agricultural watersheds (Martins et al. 2021; Fachinelli and Pereira 2023). The problem identified does not lie in the requirement for wider protection, but in the absence of sufficiently effective mechanisms to ensure its implementation, maintenance, and management. Thus, reaches with 100 m and 150 m PPAs should be treated as priority intervention areas, since they combine greater ecological importance, greater legal requirement, and greater territorial vulnerability.

5.3 Asymmetry between margins and bilateral assessment of PPAs

One of the most relevant findings of this study was the identification of asymmetry between margins in 26.7% of the sampled points. In these cases, one margin presented preserved vegetation equal to or greater than the legal minimum, or close to it, while the opposite margin maintained an expressive deficit of riparian cover. This condition demonstrates that PPA assessment based on a single margin may produce an excessively optimistic diagnosis and mask important functional losses.

From an ecological perspective, the riparian zone does not function as an isolated strip on only one edge of the channel. Its effectiveness depends on the interaction between margins, channel, adjacent plain, and land-use matrix. Classical literature describes riparian zones as dynamic ecological interfaces structured by lateral, longitudinal, and vertical flows between terrestrial and aquatic environments (Gregory et al. 1991; Naiman and Décamps 1997). When one margin remains preserved and the other is converted into pasture, cropland, or exposed area, there is loss of lateral connectivity, increased erosive vulnerability, and reduced capacity to filter sediments and nutrients.

The adoption of the limiting-margin rule constitutes a relevant methodological contribution of the study. This criterion shifts the diagnosis from a merely arithmetic logic to a functional logic: the general condition of the point must consider the most degraded margin, since it may compromise the ecological integrity of the riparian system as a whole. This approach is particularly useful in agricultural watersheds, where the coexistence of a relatively preserved margin and another intensely converted to productive use is common. In management terms, the result indicates that inspection and restoration programs should assess both margins separately and prioritize reaches in which asymmetry compromises connectivity and hydrological protection.

5.4 Confluences, crossings, and infrastructure as critical management points

Confluence areas and crossing points played a prominent role in producing the observed non-compliance. At the point associated with the confluence with the Bonfim Stream, the degradation of one margin compromised the functionality of a strategic reach for hydrological and ecological connectivity. In reaches with bridges, roads, culverts, and the ring road, exposed soil, compaction, localized erosion, vegetation suppression, and facilitation of animal access to the channel were observed.

These findings indicate that PPA management should not be limited to delimiting marginal strips on maps. It is necessary to identify critical pressure points, especially those where linear infrastructure concentrates geomorphological and hydrological impacts. Road crossings may alter surface runoff, concentrate flows, expand erosive processes, and create recurrent access for cattle and vehicles. Even when vegetation remains relatively preserved outside the immediate zone of the bridge, the functionality of the PPA may be reduced by localized but persistent impacts.

The literature on the management of riparian buffers in agricultural landscapes highlights that buffer effectiveness depends on actions directed both at the local scale and at the watershed scale (Cole et al. 2020). In this sense, the results of this study indicate that confluences and crossings should be treated as priority management units. These areas concentrate risks of erosion, silting, loss of connectivity, and sediment input into the fluvial system. Therefore, measures such as restoration of marginal vegetation, fencing, installation of water troughs outside the PPA, stabilization of trails, energy dissipators, adequate road drainage, and bioengineering solutions can produce relevant environmental gains.

5.5 Field validation and geoprocessing: methodological complementarity

The results also reinforce the importance of combining geoprocessing, remote sensing, and field validation. Previous studies have already demonstrated the usefulness of geographic information systems for delimiting PPAs, analyzing land use, and supporting environmental planning at the watershed scale (Nowatzki et al. 2010; Campagnolo et al. 2017). However, the experience in the upper Claro River shows that remote delimitation must be complemented by in situ inspection, especially when the diagnosis depends on identifying the regular channel, vegetation structure, the presence of erosion, cattle trampling, and localized interferences.

This methodological complementarity is central to environmental management. Geoprocessing allows initial screening, sampling planning, and the identification of spatial patterns. Field validation, in turn, allows recognition of functional conditions that satellite images do not always capture adequately, such as soil compaction, understory degradation, debris lines, bank instability, animal access, and localized impacts on bridges and culverts. Thus, the methodological contribution of this study lies in proposing

an integrated protocol capable of bringing legal diagnosis closer to functional ecological assessment.

The classification matrix in three categories, compliant, partially compliant, and non-compliant, proved useful for capturing intermediate gradations of the observed reality. Although the analytical tolerance of 20% has no legal basis and does not represent flexibilization of Law No. 12,651/2012, it allowed the distinction between severe non-compliance, partial preservation, and full compliance. This differentiation is relevant for management, since not all reaches require the same type of intervention. Severely degraded areas require structural restoration and immediate use control, while partially compliant areas may require management measures, fencing, assisted regeneration, and mitigation of localized impacts.

5.6 Implications for inspection, restoration, and territorial planning

The results have direct implications for the management of PPAs in agricultural watersheds of the Cerrado. The first implication is that inspection should go beyond cartographic verification of legal width. It is necessary to assess whether the protected buffer maintains continuous vegetation, functional structure, connectivity between margins, and absence of incompatible uses. The second implication is that restoration should be prioritized based on risk and functionality criteria, not merely on the abstract existence of legal liability. In the upper Claro River, reaches with 100 m PPAs, confluences, crossings, and points with asymmetry between margins should receive priority.

The third implication is the need to integrate legal instruments, territorial planning, and productive management. In rural areas, measures such as continuous fencing of the PPA, creation of alternative livestock watering points, restoration of native vegetation, control of cattle trails, and stabilization of margins can reduce direct pressures on the channel. In urban and peri-urban areas, interventions should consider licensing, maintenance of bridges and drainage systems, revegetation of banks, control of exposed soil, and mitigation of the effects of road works on the riparian buffer.

This approach is consistent with the international literature on riparian buffers, which points to the need for management oriented by ecosystem services and adapted to the local context and watershed scale (Cole et al. 2020). It also dialogues with Brazilian studies that demonstrate the importance of riparian vegetation for sediment retention,

water protection, and maintenance of environmental functions in anthropized landscapes (Nóbrega et al. 2020; Martins et al. 2021; Fachinelli and Pereira 2023). Therefore, the main applied contribution of this study is to demonstrate that the effectiveness of PPAs depends on a continuous cycle of delimitation, field verification, functional classification, prioritization of critical areas, and territorial intervention.

5.7 Study limitations and future perspectives

This study presents some limitations that should be considered. The sample of 15 points was designed to represent the longitudinal gradient of the upper course of the Claro River and different morphological and anthropogenic conditions, but it does not intend to exhaust the spatial variability of the entire basin. In addition, the field campaigns were conducted during the dry season, which favored the morphological interpretation of the regular channel, but does not allow the assessment of seasonal variations in flow, flooding, and hydrological connectivity. The functional classification was also based on visual and metric field indicators, without direct measurement of physicochemical water parameters, biodiversity, or sediment load.

Future research may increase the robustness of the diagnosis through seasonal monitoring, multitemporal image analysis, sediment modeling, water quality assessment, and incorporation of biological indicators. It would also be relevant to test the diagnostic matrix in other watersheds of the Cerrado and other Brazilian biomes in order to verify its transferability as a tool for inspection and environmental planning. Another promising agenda consists of integrating environmental registry data, land use, PPA liabilities, and restoration priorities, allowing point-based diagnoses to be transformed into territorial governance strategies.

Despite these limitations, the study offers consistent empirical evidence that legal compliance cannot be treated as automatically equivalent to riparian integrity. In the upper course of the Claro River, the formal protection of PPAs coexists with functional degradation, asymmetry between margins, agricultural and livestock pressure, and infrastructure impacts. This result reinforces the need for an integrated environmental management approach, in which the legal norm is combined with field verification, ecological restoration, productive management, and territorial planning oriented toward ecosystem functions.

6 Conclusion

This study demonstrated that legal compliance with Permanent Preservation Areas cannot be assumed to be equivalent to the ecological integrity of riparian zones. In the upper course of the Claro River, most sampled points showed deficits in preserved riparian vegetation, functional degradation, or land uses incompatible with the protective purpose of legally defined riparian buffers. The predominance of non-compliant points indicates that legally established buffer widths, although necessary, are insufficient to ensure the effective maintenance of hydrological, geomorphological, and ecological functions along river margins.

The results revealed three main patterns. First, reaches subject to wider legal buffers showed greater vulnerability to non-compliance, especially those requiring 100 m buffers and the urban reach subject to the municipal 150 m requirement. Second, asymmetry between margins showed that preservation on only one side of the channel may mask relevant functional loss on the opposite margin. Third, confluences, road crossings, bridges, cattle access to the channel, and conversion of native vegetation to agricultural or pasture use were critical drivers of riparian degradation.

The main contribution of this study is a diagnostic approach that integrates legal delimitation, field validation, bilateral assessment of river margins, and identification of anthropogenic pressures. This approach brings legal analysis closer to the effective ecological functionality of riparian buffers, providing practical support for inspection, restoration, and territorial planning in agricultural watersheds of the Brazilian Cerrado. From an environmental management perspective, priority actions should focus on reaches with wider legal requirements, asymmetric margins, confluences, and road crossings, through riparian restoration, fencing, livestock management, erosion control, and infrastructure adaptation.

Overall, the upper Claro River case reinforces a broader implication for productive tropical landscapes: legal protection is the starting point, but riparian integrity depends on material implementation in the territory. Effective protection requires continuous monitoring, field-based verification, ecological restoration, and land-use planning oriented toward ecosystem functions.

Statements and Declarations

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Competing interests

The authors declares no relevant financial or non-financial competing interests.

Ethics approval

Ethics approval was not required for this study because the research did not involve human participants, human biological material, personal data, or experimental procedures with animals.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Data availability

The datasets generated and analysed during the current study are available from the authors upon reasonable request. The field dataset includes coordinates of sampled points, altitude, regular channel width, legally required riparian buffer width, effectively preserved riparian width on each margin, diagnostic classification, field notes, and photographic records.

Author contributions

José Renato Nascimento Tiraboschi Filho contributed to the conceptualization, methodology, field survey, data organization, legal and environmental analysis, writing of the original draft, and review and editing of the manuscript.

Pedro França Júnior contributed to research supervision, methodological guidance, field survey, interpretation of field data, and review and editing of the manuscript.

All authors read and approved the final manuscript.

Use of AI-assisted tools

AI-assisted tools were used to support language revision, structural organization, and manuscript editing. The authors reviewed, verified, and take full responsibility for the final content of the manuscript.

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