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Connection between riparian vegetation and water quality

THE CONNECTIONS BETWEEN RIPARIAN VEGETATION AND WATER QUALITY IN THE ATLANTIC FOREST

Lucas Abbadi Ebling[1*] & *Andre Andrian Padial*[1,2]

[1]Universidade Federal do Paraná, Setor de Ciências Biológicas, Departamento de Botânica, Programa de Pós-graduação em Ecologia e Conservação, Laboratório de Análise e Síntese em Biodiversidade, Av. Cel. Francisco H. dos Santos, 100, CEP 81530-000, Curitiba, PR, Brasil

[2] Universidade Estadual de Maringá, Núcleo de Pesquisa em Limnologia, Ictiologia e Aquicultura, Programa de Pós-graduação em Ecologia de Ambientes Aquáticos Continentais, Av. Colombo, 5790, CEP 87020-900, Maringá, PR, Brasil.

E-mails: lucasbio201@gmail.com ([*]Corresponding author); aapadial@ufpr.br

ABSTRACT: The vegetation near water bodies constitutes the primary component of riparian zones, and its significance for the health and maintenance of aquatic ecosystems is widely acknowledged. Degradation of riparian vegetation constrains the capacity of environments to serve as buffers against the influx into water bodies of contaminants and nutrients resulting from human activities, thereby directly exerting a negative impact on water quality. Here, we conducted a systematic review of studies focused on the effect of riparian vegetation on the environmental quality of aquatic ecosystems within the Brazilian Atlantic Forest. Between 2000 and 2023, a total of 421 articles were identified, accessible through platforms such as Web of Science (Thomson Reuters), Scopus (Elsevier), and the 'Portal Periódicos da CAPES'. 24 articles fit within the criteria of our investigation, and all indicated the importance of riparian vegetation to aquatic bodies. Riparian vegetation was directly examined in 91% of the studies. The majority of studies on freshwater aquatic ecosystems were conducted in streams. 70% of the publications employed biological groups as response variables, and benthic macroinvertebrates were the most frequently studied group. There was a clear trend of research growth. Given the myriad threats and pressures confronting the Atlantic Forest due to disruptive land uses and associated anthropogenic activities, studies assessing the conservation of riparian vegetation and its correlation with water quality in this biome are very informative. In future studies, other biodiversity parameters could be used, such as functional diversity, in association with water quality and the functioning of freshwater ecosystems. Assessing the presence of invasive species in the composition of riparian vegetation could also be evaluated to determine if it directly affects water quality. Such efforts are vital for safeguarding water resources and preserving the ecosystem services furnished by aquatic ecosystems.

Keywords: Aquatic ecology; ecosystem services; limnology; water resources.

INTRODUCTION

The riparian zone of continental aquatic ecosystems exhibits high spatial and temporal variability, influenced by bioclimatic, geomorphological, and land use conditions, which can change over time due to both natural and anthropogenic factors (Riis et al., 2020; Bonfoey et al., 2023). Such zones provide physically dynamic and biologically diverse environments, spanning watercourses ranging from large rivers to small streams (Rood et al., 2020; Ferreira et al., 2023). Riparian zones create gradients of environmental conditions, ecological processes, and plant communities, serving as ecotones between terrestrial and aquatic environments (Prado et al., 2022).

Given that vegetation constitutes the primary component of riparian zones, its significance for the health and maintenance of aquatic ecosystems is widely acknowledged (Naiman et al., 2005; Carmo et al., 2023; Majumdar & Avishek, 2023). The presence of riparian vegetation contributes to various ecosystem services crucial for biodiversity (Clerici et al., 2014; Petsch et al., 2023). Riparian vegetation provides provisioning services promoting genetic resources and biomass, regulatory services by filtering pollutants and other chemicals from water systems, carbon sequestration, erosion control, water flow regulation, microclimate regulation, and direct and indirect cultural services (Riis et al., 2020; Prado et al., 2022).

Despite its significance, riparian vegetation has undergone extensive degradation in Brazil (Celentano et al., 2017; Ramos et al., 2023). The removal of riparian vegetation for land use purposes, such as agriculture and livestock farming, poses a major threat (Hughes and Vadas-Jr, 2021; Piczak et al., 2023). Negative impacts on aquatic ecosystems include increased gross primary productivity in water bodies and alterations in bacterial and fungal assemblages in the soil, potential elevation in denitrification rates, and sedimentation (Tolkkinen et al., 2020). Moreover, the degradation of riparian zones diminishes the capacity of such ecotones to act as biological buffers against the influx of contaminants, sediments, and nutrients from human activities into aquatic ecosystems (Fierro et al., 2017; Wu et al., 2023). It is thus consensus that riparian vegetation significantly influences water quality in aquatic systems (Souza et al., 2013).

The Atlantic Forest biome is the second largest forest in South America and one of the most biodiverse, as well as one of the most threatened and important for conservation (Marques et al., 2021). Recognized as one of the 25 global biodiversity hotspots, the Atlantic Forest is a dense ombrophilous forest with various formations, including coastal (3 to 50 m), submontane (50 to 500 m), montane (500 to 1,200 m), and high-montane (1,200 to 1,400 m) forests (Faoro et al., 2010). Much of the pressure on this biome is due to the loss of native vegetation resulting from natural resource exploitation (Lira et al., 2021). Currently, the Atlantic Forest is highly fragmented, with the remaining coverage represents only 12.4% of its original extent (Santos et al., 2018). In light of these impacts, there is an urgent need for conservation, restoration, and habitat preservation to maintain the biodiversity of the Atlantic Forest (Ribeiro et al., 2009).

We conducted a systematic review of studies on the effect of riparian vegetation on water quality and aquatic ecosystem integrity in the Brazilian Atlantic Forest, and here we describe the primary water quality parameters addressed in these studies. We also outline future perspectives for developing studies on the connections between riparian vegetation and water quality in freshwater ecosystems in the Brazilian Atlantic Forest.

METHODS

This systematic and scientometric review was conducted in two stages. In the first stage, data collection involved searching for scientific articles that addressed the relationship between water quality and riparian vegetation within the Atlantic Forest Biome. Searches were conducted on the Web of Science (Thomson Reuters), Scopus (Elsevier), and CAPES Periodicals Portal platforms. We included only scientific articles published in English from January 2000 to December 2023, and for the article searches, we used the following keywords with boolean operators: (riparian vegetation* OR buffer* OR zone*) AND (water quality* OR pollution* OR integrity*) AND (Atlantic Forest* OR Brazilian Forest* OR Subtropical Forest*). We excluded reviews, opinion papers, abstracts from scientific events, short research notes, book chapters, dissertations, and theses. In the second stage, we conducted a scientometric analysis by evaluating the articles resulting from the search. The selection of the articles used in this study, we followed the PRISMA protocol for systematic reviews (Page et al., 2021). We initially analyzed the titles and abstracts of the articles, then proceeded to read them in full.

We considered only studies conducted in freshwater ecosystems, such as rivers, streams, lakes, and others. We included studies that assessed physical, chemical, and biological parameters of aquatic ecosystems as indicators of water quality. For physical parameters, variables such as turbidity (NTU), temperature (°C), color, taste and odor, solids (mg/L), and electrical conductivity (µS/cm) were cited in articles. Regarding chemical parameters, we considered variables such as pH, dissolved oxygen (mg/L), alkalinity (mg/L), chloride (mg/L), chlorine residual (mg/L), sulfate (mg/L), nitrogen (mg/L), fluoride (mg/L), iron (mg/L), manganese (mg/L), copper (mg/L), carbon (mg/L), zinc (mg/L), hardness (mg/L), biochemical oxygen demand (mg/L), toxic organic and inorganic substances, and radioactive substances. For biological parameters, we considered studies that assessed indicator groups of water quality, such as phytoplankton, zooplankton, and macroinvertebrates. We also made a word cloud using the keywords of selected articles to demonstrate the main trends in publications.

RESULTS

During the period between 2000 to 2023, we identified a total of 421 articles. Among these, 382 (90%) articles were accessible through the Portal de Periódicos da CAPES (CAPES Periodicals Portal), 36 (9%) articles were found on the Web of Science platform (Thomson Reuters), and three (1%) articles were located on the Scopus platform (Elsevier).

Among the 421 publications, we identified 24 articles related to the scope of our study (Figure 1). We observed that over the study period, there was an increase in publications starting from the year 2016 (two articles - 8%), with the highest number of publications occurring in 2018 (seven articles - 29%) (Figure 2).

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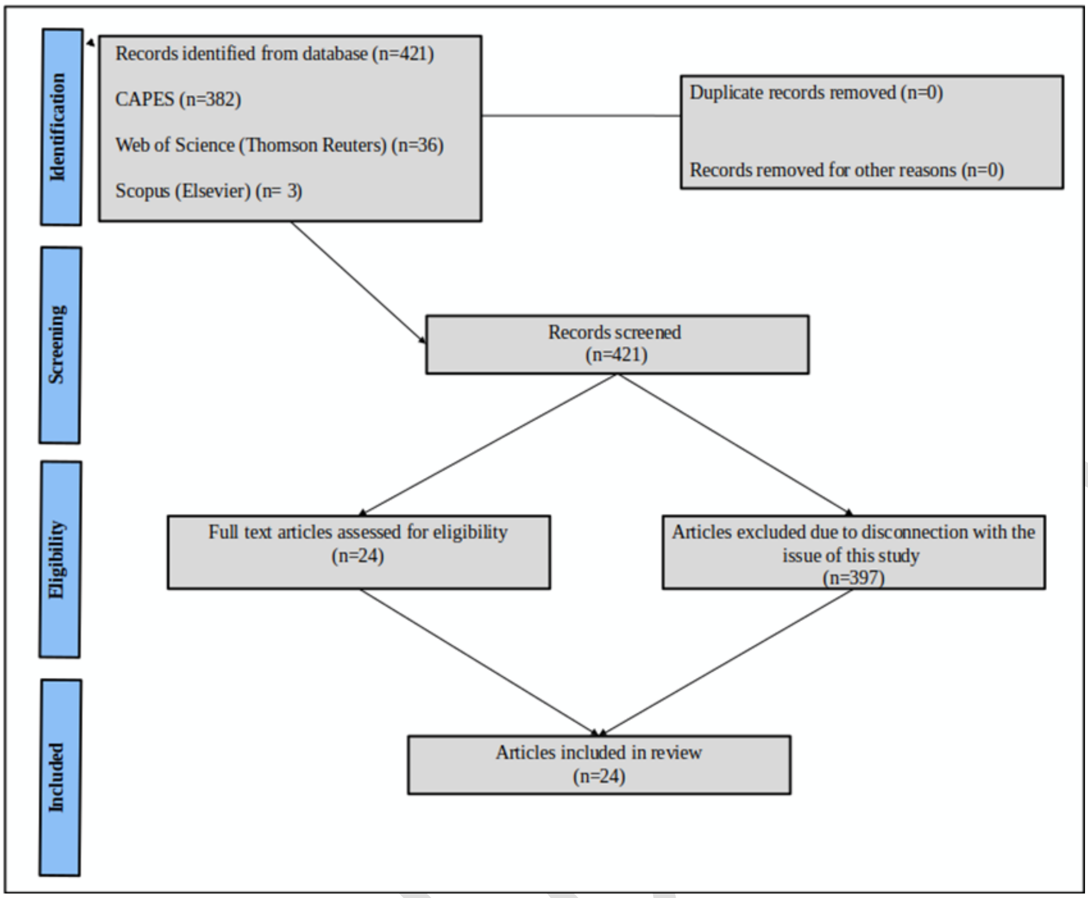

Figure 1. The scheme employed to select articles obtained in the search was based on the PRISMA protocol (Page et al., 2021).

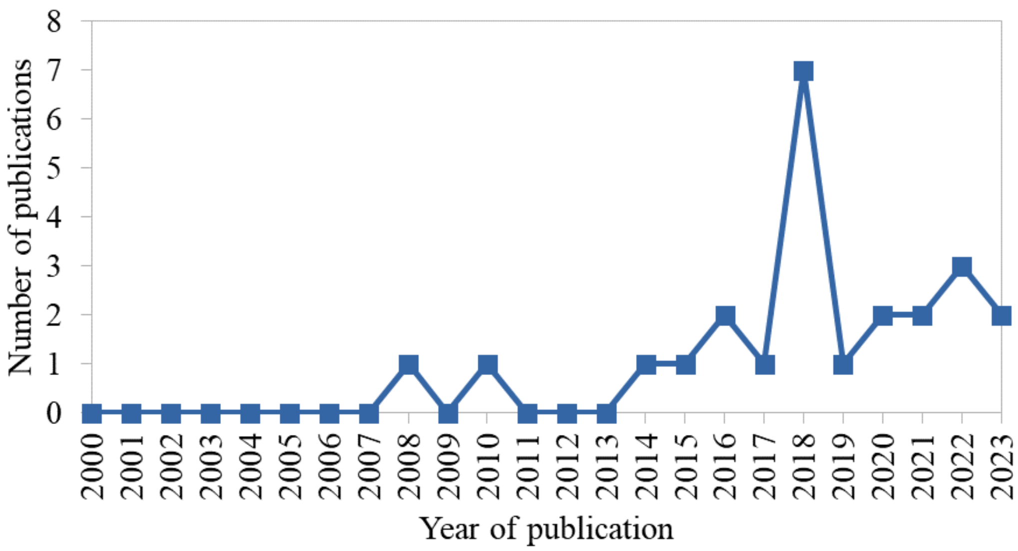

Figure 2. Number of publications addressing the relationship between water quality and riparian

vegetation within the Atlantic Forest Biome between 2000 and 2023.

São Paulo (SP) and Rio Grande do Sul were the Brazilian states with the highest number of studies, both with eight publications each (33%), while Santa Catarina (SC) and Rio de Janeiro (RJ) had three publications each (12%), Minas Gerais (MG) and Paraná (PR) had the one publication each (4%). No other studies on this topic were found in other states within the Atlantic Forest biome. The most frequent keywords in the articles (larger font in purple) were forest, occurring in 11 publications, followed by water, appearing in seven publications, and the words cover, land, and riparian were common in six publications (Table 2S; Figure 3).

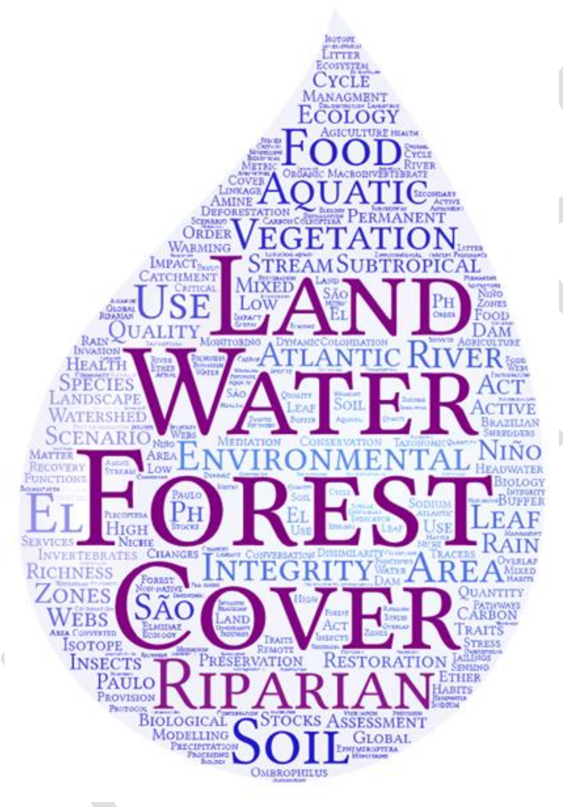

Figure 3. Word cloud with keywords from articles selected for the review, see methods for selection criteria. The most frequent keywords are highlighted in purple.

We observed that journals with the highest numbers of publications were Acta Limnologica Brasiliensia, with four publications (16%), followed by Science of the Total

Environment, with three publications (12%), and Annals of the Brazilian Academy of Sciences, with two publications (8%) (Table 1).

Table 1. Number of publications per journal among the 24 selected articles reviewing the relationship between water quality and riparian vegetation within the Atlantic Forest Biome (see methods for article selection criteria).

Journals	Number of publications
Acta Limnologica Brasiliensia	4
Science of the Total Environmental	3
Anais da Academia Brasileira de Ciências	2
Brazilian Journal of Biology	1
CERNE	1
Ecological Applications	1
Ecological Indicators	1
Entomological Science	1
Environmental Biology of Fishes	1
Floresta	1
Hydrobiologia	1
Hydrological Process	1
Irriga	1
Journal of Limnology	1
Limnology	1
Marine and Freshwater Research	1
Perspectives in Ecology and Conservation	1
Water	1

All articles indicated the importance of Riparian vegetation to environmental quality of water bodies, but they used different approaches and evaluated different metrics. Riparian vegetation was directly assessed in 91% of the publications (22 articles). In these studies, land use and land cover in the riparian zone were measured using geographic information systems. In

16 of these publications, freshwater ecosystems were classified as natural or impacted using landscape features. Freshwater ecosystems classified as impacted were those where the percentages of land uses associated with human activity in riparian zones exceeded native vegetation cover. The main land uses and land cover addressed in these studies were agriculture, pasture, urbanization, mining, forestry, and bare soil (Table 1S - Supplementary Material). In the remaining six publications, freshwater ecosystems were not categorized by land use, and the riparian zone was analyzed using the percentage of vegetation cover. One of these publications examined the presence of invasive species in the riparian zone.

Riparian vegetation was not directly assessed in 8% of the publications (two articles). In these experimental cases, the riparian zones used in these studies had the presence of invasive species, and the authors aimed to understand the process of leaf litter decomposition of native and exotic species in water bodies. The decomposition experiments conducted in the water bodies in these studies simulated ecological conditions for the input of organic matter from invasive species.

Water physical parameters were analyzed in 75% of the publications (18 articles, Table 1S). Water temperature and electrical conductivity were the most frequently analyzed physical variables, both examined in 15 publications, followed by turbidity and water velocity, each addressed in six publications. Dissolved solids, water depth, and stream size were addressed in four publications. On the other hand, the physical variables with the lowest number of mentions among the studies were water color, analyzed in two publications, and water taste and odor, addressed in one publication.

Chemical parameters were analyzed in 83% of the publications (20 articles, Table 1S). The chemical variables examined in these studies included pH, dissolved oxygen, alkalinity, chloride, nitrate, phosphate, sulfate, nitrogen, manganese, copper, zinc, cadmium, lead, sodium, potassium, ammonium, phosphorus, calcium, magnesium, total carbon, organic and inorganic carbon, and hardness. The most frequently addressed chemical variables in the studies were dissolved oxygen, analyzed in 15 publications, and pH, analyzed in 12 publications. Nitrogen was analyzed in seven publications. Nitrate was addressed in six publications. Total carbon was analyzed in five publications.

The majority of the studies (70%, 17 articles) were conducted in streams (Table 1S), while in 12% of the publications (three articles), studies were conducted in rivers, and other 12% of the publications, research was conducted at the watershed level without evaluating of the nature of the water body. One study considered both streams and rivers.

Taxa as response variables were addressed in 70% of the publications (17 articles). Among them, the biological groups included total and thermotolerant coliforms, algae, periphyton, macrophytes, benthic macroinvertebrates, and fish (Table 1S, Figure 4). In all studies that used biological groups, physical and chemical water variables were also measured, such as water temperature, turbidity, electrical conductivity, nitrite and total phosphorus concentrations, dissolved organic carbon, and total dissolved nitrogen. In these studies, the water environmental variables were used to characterize the environment and relate them to the distribution and structuring of biological communities.

The most studied biological group was benthic macroinvertebrates, analyzed in 12 studies. In six publications, macroinvertebrates were examined based on a broad distribution of groups, ranging from Annelida to Diptera. In four publications, only bioindicator groups (e.g., Ephemeroptera, Plecoptera, and Trichoptera) were used. In two publications, a specific bioindicator group (e.g., Elmidae) was analyzed (Figure 5).

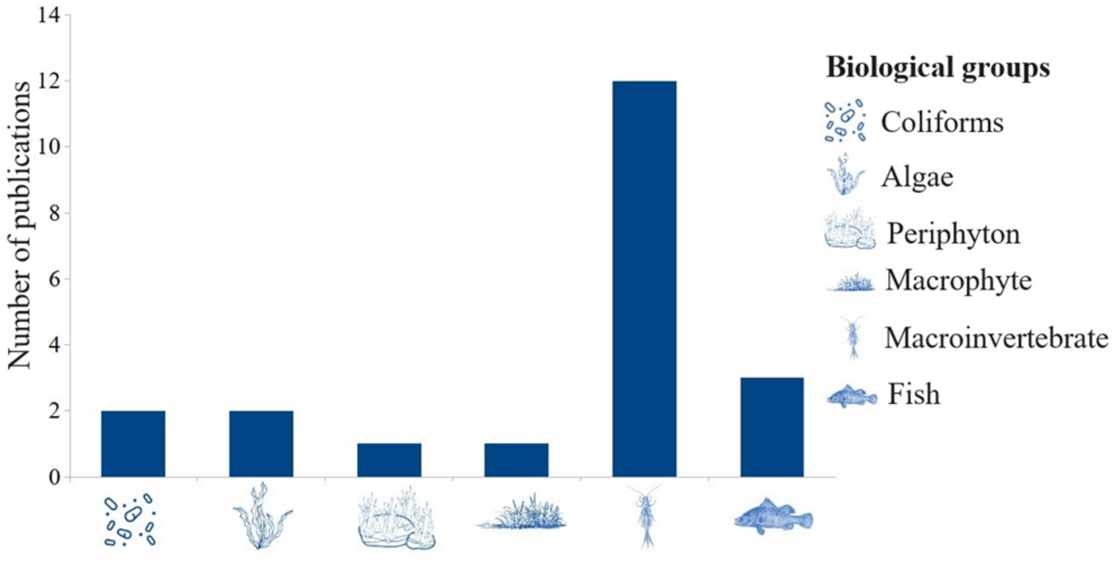

Figure 4. Biological groups analyzed in articles selected for the review, see methods for selection criteria.

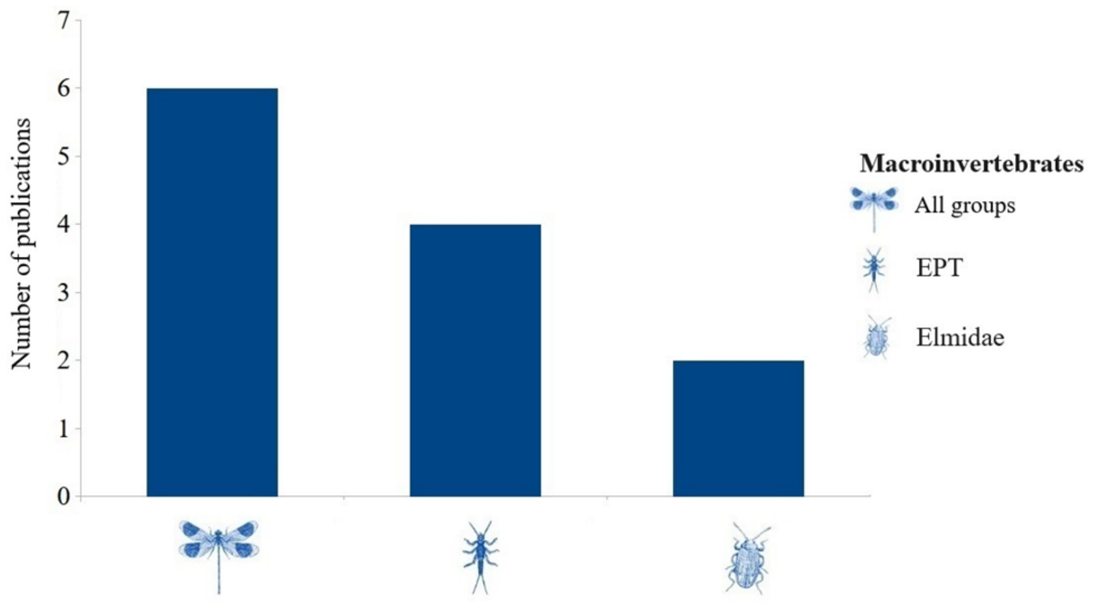

Figure 5. Macroinvertebrates groups analyzed in articles selected for the review, see methods for selection criteria. *EPT = Ephemeroptera, Plecoptera, and Trichoptera.

On the other hand, we observed that in 29% of the publications (7 articles), biological groups were not used as response variables of disturbances. In five of such publications, only physical and chemical parameters were considered, while in the other two publications, other environmental parameters such as vegetation cover and percentages of land use associated with human activities (*e.g.* agriculture and pasture) were considered.

DISCUSSION

Our aim was to conduct a systematic and scientometric review of research conducted in the Atlantic Forest investigating the relationships between riparian vegetation and water quality. Our findings revealed a growing interest in the topic, but still a paucity of studies in several Brazilian states with the Atlantic Forest biome. We can infer that the growing interest in studying the riparian vegetation in the Atlantic Forest and its associations with water bodies was propelled by the ongoing destruction and conversion of this biome for land uses linked to anthropogenic activities (Abreu et al., 2022; Caballero et al., 2022). The revised articles revealed a consensus on the negative impacts of removing Riparian vegetation on the environmental quality of aquatic ecosystems.

A myriad of natural factors may influence water quality including landscape, hydrological, atmospheric, climatic, topographic, and lithological factors (Rissmann et al., 2023). Anthropogenic activities that negatively affect water quality include mining, livestock farming, industrial and urban waste production and disposal, increased sediment runoff, soil erosion due to changes in land use, and pollution from heavy metals (Häder et al., 2020; Mello et al., 2020; Yuan et al., 2023). It is clear that the replacement of native forests with areas designated for human activities is a problem affecting not only the Atlantic Forest but ecosystems worldwide (Ditt et al., 2010; Newbold et al., 2015; Caballero et al., 2022). The landscape changes for anthropogenic activities in areas of native vegetation affect and compromise the conservation of riparian vegetation and consequently the environmental quality of water bodies (Borisade et al., 2021; Kantharajan et al., 2023). Without vegetative cover surrounding water bodies, the health of these ecosystems is compromised, impacting the biota inhabiting these areas and consequently the ecosystem processes occurring in these environments (Tonello et al., 2021; Zeng et al., 2022). We indeed highlight that studies warn of the negative effects of removing vegetative cover from the riparian zone on the integrity of freshwater ecosystems, affecting soil stability, sediment capture, temperature and organic matter control, flood regulation, and biodiversity (see also Manning et al., 2020).

Indeed, we observed that studies directly assessing riparian vegetation (91%) opted to classify the aquatic ecosystems as impacted when the local land use associated with anthropogenic activities exceeded the remaining area of riparian native zones, and as not impacted natural otherwise (Breda et al., 2021; Machado-Silva et al., 2022). In this context, studies involving changes and conversion of native riparian vegetation tend to evaluate the proportion of the remaining native riparian vegetation in relation to established rural areas within the study area. (Tavares et al., 2019; Preto et al., 2022).

Evaluating water quality is a crucial tool for assessing the health of aquatic ecosystems (Häder et al., 2020; Yuan et al., 2023). Presently, water quality stands as one of the most central and debated topics, directly intertwined with public health concerns (Shahsavani et al., 2023). Water quality degradation is influenced by various factors, including natural processes, anthropogenic activities, and intensified exploitation of water resources, and represents a global-scale issue (Uddin et al., 2021; Wu et al., 2023). In line with this rationale, we observed that the physical and chemical parameters of water were thoroughly assessed in the majority of publications.

There was a wide array of biological groups used in the studies that ranged from coliforms to fish, and indeed most studies considered biological groups as indicators to access of impacts in the riparian vegetation. The effects of riparian vegetation on biological groups are widely recognized in the literature. In its absence, there is an increase in sunlight exposure, water temperature, and nutrient concentrations, favoring a higher number of algae, periphyton, and macrophyte species (Hlúbiková et al., 2014; Allan et al., 2021). Conversely, the presence of riparian vegetation affects the composition of macroinvertebrate and fish communities (Fierro et al., 2017; Manoel & Uieda, 2021; Sargac et al., 2021). The use of biological groups supports in understanding the effects of various disturbances and pollutants on aquatic ecosystems, serving as an effective tool to assess the water quality of these environments (Attrill & Depledge, 1997; Aqel et al., 2024). Biological groups can be employed in various ways to evaluate the water quality of freshwater ecosystems (O'Brien et al., 2016; Liu et al., 2023). For instance, microbiological indicators of water quality can be used to assess the presence of a species or group of microorganisms that enter aquatic systems through fecal matter, posing a risk to human health (Holcomb & Stewart, 2020; Vucinic et al., 2023). Algae, on the other hand, can be used to assess issues related to eutrophication, acidification, and salinization in freshwater ecosystems (Charles et al., 2021; Zabaleta et al., 2023). Macrophytes, due to their sedentary lifestyle and relatively slow growth, can serve as long-term indicators of the health status of freshwater ecosystems, particularly lakes, as this group is crucial for monitoring nutrient enrichment in the land-water ecotone (Zhang et al., 2013; Grzybowski et al., 2023). Fish are widely used in biomarker analyses of genotoxicity to examine the adverse effects of exposure to pollutant levels in freshwater ecosystems (Bolognesi & Cirillo, 2014; Ghaffar et al., 2021; Muzaffar et al., 2023; Silva et al., 2023).

It is indeed expected that the most addressed biological group in the publications was benthic macroinvertebrates. The predominance of studies related to benthic macroinvertebrates, riparian vegetation, and water quality can be attributed to several factors: i) the low economic cost associated with the collection of macroinvertebrates, which does not require expensive and sophisticated equipment (Stark et al., 2001; Ramírez et al., 2023); ii) the known sampling methods for macroinvertebrates, as they are ubiquitous in almost all freshwater environments

(Kenney et al., 2009; Eriksen et al., 2021; Simaika et al., 2024); iii) the well-consolidated taxonomic knowledge, with various identification keys available in English, Portuguese, and Spanish (Fernandez & Domingues, 2001; Mugnai et al., 2010; Hamada et al., 2018); iv) the fact that relationships between riparian vegetation, water quality, and macroinvertebrates are widely recognized and disseminated in the literature (Rios & Bailey, 2006; Fierro et al., 2017; Palt et al., 2022); v) and probably most importantly, the fact that macroinvertebrates are considered bioindicators of water quality, as different taxa exhibit varying degrees of sensitivity to pollution and other impacts (Eriksen et al., 2021; Sripanya et al., 2023).

Some publications that incorporated macroinvertebrates in their studies encompassed the entire diverse spectrum of the group, including Diptera, Odonata, Gastropoda, among others. Other studies focused solely on bioindicator groups, such as the orders Ephemeroptera, Plecoptera, and Trichoptera. There are various methodologies for analyzing benthic macroinvertebrates and correlating them with water quality and riparian vegetation (Stone et al., 2005; Smith et al., 2007; Miserendino et al., 2012; Sripanya et al., 2023). One of the most established approaches involves the use of biotic indices of water quality, such as the Family Biotic Index and the Biological Monitoring Working Party (BMWP) and its variations, alongside other indices (Walley et al., 1997; Paisley et al., 2014; Cárdenas-Castro et al., 2018; Magbanua et al., 2023). Such indices assign numerical values to various taxa based on their sensitivity and tolerance to pollutants and other contaminants (Kumari & Maiti, 2020; Etriieki & Küçükbasmacı, 2024).

Regarding biological groups, the publications focused solely on taxonomic aspects, such as species abundance and richness. However, other metrics can be applied in future studies to investigate the relationship between biological groups, riparian vegetation, and water quality in the Atlantic Forest. One such metric is functional diversity, through which it is possible to measure functional richness (FRic), functional evenness (FEve), functional divergence (FDiv), and functional dispersion (FDis) based on functional traits (Laliberté & Legendre, 2010).

Functional traits for aquatic organisms such as macrophytes, macroinvertebrates, and fish are well-known (Heino, 2005; Vecchia et al., 2020; Lin et al., 2021). For macrophytes, functional traits such as life form (e.g., free-floating, submerged, anchored), morphology (*e.g.* leaf area and growth morphology), and dispersal can be measured (Stefanidis & Papastergiadou, 2019; Vecchia et al., 2020). For macroinvertebrates, functional traits include body length, predator mandible size, life cycle duration, potential number of life cycles per year, aquatic stages, dispersal, locomotion, and feeding habits (Heino, 2005; Coccia et al., 2021). For fish, functional traits related to feeding type, reproductive strategy, habitat preferences, and migration can be used (Mueller et al., 2013; Lin et al., 2021). By applying the functional diversity approach, it is possible to gain insights into ecosystem processes in aquatic environments and associate these with water quality metrics (Stefanidis & Papastergiadou, 2019; Lin et al., 2021).

Another perspective for future studies in the Atlantic Forest is the assessment of invasive species presence in riparian vegetation. In our findings, only one publication evaluated the presence of invasive species in riparian vegetation and their effects on water bodies. This is a current and persistent topic in ecology, as invasive species alter and influence the entire ecosystem's functioning (MacDougall & Turkington, 2005; Didham et al., 2007; Britton, 2023). The presence of invasive species in riparian vegetation leads to a homogenization of community composition due to their high dispersal and reproductive capacity (Fontana et al., 2022; Gui et al., 2023). Consequently, the effects of invasive species on aquatic ecosystems may influence water quality (Henry et al., 2023; McKendrick et al., 2024). Geoprocessing tools and satellite imagery can assist in identifying invasive species in riparian vegetation (Majumdar & Avishek, 2023; Mallmann et al., 2023). Through this conceptual and methodological framework, it would be possible to assess how invasive species act and influence water quality in the Atlantic Forest's water bodies.

CONCLUSIONS

Given the manifold threats and pressures confronting the Atlantic Forest due to disruptive land uses associated with anthropogenic activities, it is imperative to conduct studies assessing the conservation of vegetation in riparian zones within this biome. The available knowledge on the subject provide a scientific consensus on the positive effects of keeping Riparian vegetation on aquatic ecosystems. Such endeavors are crucial for safeguarding water resources and preserving the ecosystem services rendered by these aquatic environments. Nonetheless, our results indicate a still paucity of studies considering several features including a larger representation of sites and biological groups.

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Supplementary Material

Table 1S. Articles used in this review, see methods for selection criteria. * MG= Minas Gerais; RJ= Rio de Janeiro; RS= Rio Grande do Sul; SP= São Paulo; SC= Santa Catarina; PR= Paraná.

Table 2S. Most frequently used words in the keywords of the articles reviewed, see methods for selection criteria.

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