

Leaf Litter Decomposition as a Functional Indicator of Stream Health: Evidence of Non-linear Responses Along Land Use Gradients in Tropical Streams

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Research Article

Keywords: Environmental integrity, Ecosystem processes, Land-use intensity

Posted Date: September 10th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10541379/v1>

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Additional Declarations: No competing interests reported.

Abstract

Leaf litter decomposition is a key ecosystem process in headwater streams and a sensitive indicator of environmental change. However, its response to anthropogenic disturbance in tropical systems remains poorly understood, particularly along continuous gradients of environmental integrity. In this study, we evaluated leaf litter decomposition across 48 sites in Cerrado streams (Brazil), using coarse- and fine-mesh litterbags to disentangle biotic contributions. We tested how decomposition responds to gradients of stream health (Tropical Water Health Index - TWHI) and land use intensity (LUI), and assessed the relative influence of physicochemical variables and biological components. Decomposition exhibited a clear non-linear (unimodal) response along both TWHI and LUI gradients, with highest rates occurring at intermediate levels of disturbance. Electrical conductivity and temperature were the main environmental predictors, indicating the importance of nutrient availability and metabolic regulation. Decomposition was strongly associated with macroinvertebrate abundance, particularly EPT taxa, and fungal biomass. These findings demonstrate that ecosystem functioning in tropical streams is shaped by the balance between resource-driven stimulation and biodiversity loss, resulting in non-linear responses to disturbance. By linking decomposition to continuous measures of environmental integrity, this study highlights the value of functional indicators for detecting complex ecological responses and improving biomonitoring and management strategies in freshwater ecosystems.

Introduction

Freshwater ecosystems are increasingly shaped by diffuse and interacting anthropogenic pressures, particularly in tropical regions where land-use change and urban expansion are rapidly transforming watershed structure and function (Tanaka et al., 2021; Fernández et al., 2021; Mosquera et al., 2026). These pressures alter fundamental environmental gradients, such as nutrient availability, thermal regimes, and habitat complexity, thereby reshaping both community composition and ecosystem processes (Fernandes et al., 2021; Viza et al., 2024). Understanding how ecological functioning responds to such gradients remains a central challenge in stream ecology, especially under scenarios where multiple drivers operate simultaneously and non-linearly (Allan, 2004; Townsend et al., 2008).

Leaf litter decomposition is a core process in headwater streams, linking riparian inputs to energy flow and nutrient cycling (Graça et al., 2015; Robbins et al., 2023). It emerges from the combined activity of microbial decomposers and detritivorous macroinvertebrates, and is regulated by environmental constraints that operate across spatial scales, from local physicochemical conditions to landscape-level land use (Graça et al., 2015; Ferreira et al., 2016; Oester et al., 2026). Because of this integrative nature, decomposition has been widely used as a functional indicator of ecosystem condition (Young et al., 2008; Tiegs et al., 2019; Ferreira et al., 2021). However, its response to environmental change is not always straightforward. While nutrient enrichment and moderate disturbance can stimulate microbial activity and accelerate decomposition (Ferreira et al., 2015), more intense degradation may suppress biological communities (Castro et al., 2025) and reduce process rates, suggesting the potential for non-linear responses along disturbance gradients (Wiederkehr et al., 2020; Pérez et al., 2023).

Recent developments in freshwater assessment have introduced continuous metrics of environmental integrity, such as the Land Use Intensity index (LUI) and the Tropical Water Health Index (TWHI), which integrate multiple dimensions of anthropogenic pressure and ecosystem condition (Campos et al., 2024; Zeni et al., 2025). These indices provide an opportunity to explicitly test how ecosystem processes respond along continuous gradients, rather than across discrete categories (Allan, 2004; Feld et al., 2011). However, the extent to which functional processes such as decomposition track these gradients linearly (García et al., 2025), and at which levels of disturbance they begin to exhibit unimodal responses, remains poorly understood.

Here, we examine leaf litter decomposition across a continuous gradient of environmental integrity in tropical Cerrado streams, explicitly linking ecosystem functioning to landscape-scale drivers and local environmental conditions. We assess how decomposition responds to variation in stream health (TWHI) and land-use intensity (LUI), identify the key physicochemical drivers associated with process rates, and evaluate the relative contribution of microbial and macroinvertebrate components along the gradient. We hypothesize that decomposition exhibits a non-linear response to environmental degradation, reflecting the interaction between nutrient-driven stimulation and biodiversity-mediated constraints. Furthermore, we expect that environmental drivers such as temperature and conductivity modulate these responses, while shifts in biological assemblages mediate the translation of environmental change into ecosystem functioning. By integrating functional processes with continuous measures of environmental integrity, this study advances a gradient-based perspective on ecosystem functioning in tropical streams. More broadly, it contributes to bridging the gap between structural indicators and ecological processes, providing a framework for interpreting how multiple stressors jointly shape ecosystem functioning under ongoing environmental change (Allan, 2004; Feld et al., 2011).

Materials and methods

Study area

The study was conducted in the Federal District and the state of Goiás (Brazil), encompassing 36 streams. Of these, seven streams had more than one sampling site, resulting in a total of 48 sampling sites (Fig. 1). The analyzed streams are up to third order and belong to three different hydrographic basins: Maranhão, Paranaíba, and Preto.

The study area is located within the Cerrado biome, which is characterized by savanna vegetation, with formations ranging from open grasslands to dense riparian forests. The regional climate is seasonal, with a rainy season from October to April and a dry season from May to September. Mean annual temperature is approximately 20°C, and annual precipitation is around 1,700 mm, with rainfall concentrated during the warmer months. Soils are generally acidic and nutrient-poor but support high plant species diversity associated with different phytophysiognomies (Eiten, 1972).

The streams exhibit natural vegetation cover along their margins, ranging from 40% to 100%, with higher percentages observed in streams located within protected areas. Stream elevation ranges from 744 to 1,220 meters. These streams drain both natural areas and regions with human occupation and agricultural activities; information on land use within the drainage basins was obtained through geoprocessing analyses from Campos (2021).

Stream characterization

Field collections, analyses and experiments were conducted between August and September 2018 by Campos (2021). In all streams, dissolved oxygen concentration and water temperature were measured directly in the field using portable probes. Water samples were collected for laboratory analyses, in which pH and electrical conductivity were measured using a benchtop meter (pH/conductometer, Metrohm 914), and turbidity was measured using a turbidimeter (Quimis ISO 9001, model Q279P). Current water velocity was determined using a flow meter (Swoffer Instruments, model 3000). Water samples were also collected for chromatographic analyses of cations and anions (Metrohm 930 IC). For the present study, only nitrate and phosphate concentration data were used, as they represent the main bioavailable inorganic forms of nitrogen and phosphorus directly assimilable by the microbial community.

Description of the Leaf Litter Decomposition Experiment

For the leaf litter decomposition experiment, portions of approximately 3g of leaves from the species *Hyeronimia alchorneoides* Allemão were weighed. Leaves were collected during the dry season, prior to the beginning of fieldwork. The leaves were placed in coarse-mesh litterbags (10 mm mesh size) and fine-mesh litterbags (0.5 mm mesh size), the latter excluding the influence of macroinvertebrates. At each sampling site, six litterbags were incubated, consisting of three coarse-mesh and three fine-mesh bags, arranged alternately so that they remained fully submerged within the streambed substrate for an incubation period of approximately 30 days, as described by Campos (2021).

Laboratory Procedures

Detritus Processing

After the incubation period, the litter bags were retrieved and transported to the laboratory. Leaves were gently rinsed with distilled water to remove sediments and associated macroinvertebrates over a 0.5 mm mesh sieve, allowing their separation for subsequent identification. From each leaf sample, 10 mm diameter discs were excised and used for ash-free dry mass (AFDM) determination and for ergosterol and adenosine triphosphate (ATP) analyses.

The set of discs designated for weighing was placed in a muffle furnace at 500°C, where high temperatures combusted the organic compounds, leaving only inorganic material. Thus, by subtracting ash mass from total dry mass, the organic fraction of the sample (ash-free dry mass, AFDM) was obtained. The remaining leaf material was then oven-dried at 60°C and subsequently weighed. The dry mass of the remaining leaf material was added to the mass of the excised discs, resulting in the final sample mass. Using the initial and final masses, leaf mass loss during the incubation period was calculated, and the decomposition rate constant (k) was estimated.

Extraction and Quantification of Ergosterol and ATP

Fungal biomass associated with the leaves was estimated based on ergosterol concentration (Gessner, 2020). For lipid extraction, three leaf discs were placed in a potassium hydroxide–methanol solution (KOH/methanol, 8 g L⁻¹) and incubated in a water bath. Using a vacuum manifold, the extract was transferred to a solid-phase extraction (SPE) column, and ergosterol was subsequently eluted with isopropanol. Quantification was performed by chromatography using an HPLC system (DIONEX Summit P580, Sunnyvale, CA, USA), and results were expressed as µg ergosterol g⁻¹ AFDM.

The ATP extraction process begins with the homogenization of leaf discs in a mixture of sulfuric acid, oxalic acid, and HEPES solutions. The mixture is then centrifuged to separate the solids from the liquid fraction containing the extracted ATP. The resulting supernatant is filtered to remove impurities, and the pH is adjusted to 7.0–7.5. The solution is stored in vials and frozen until ATP measurement. After extraction, ATP is quantified by bioluminescence using a luminometer, and results are expressed as nmol ATP g⁻¹ AFDM (Abelho et al., 2005).

Sorting and Identification of Macroinvertebrates

Macroinvertebrates associated with the litterbags were preserved in glass vials containing 70% ethanol. Sorting and identification were conducted exclusively in the present study, up to the taxonomic level of Order, using the identification manual *Insetos aquáticos na Amazônia brasileira: taxonomia, biologia e ecologia* [Aquatic insects of the Brazilian Amazon: taxonomy, biology, and ecology]. In this study, only the orders Ephemeroptera, Plecoptera, and Trichoptera (EPT) were considered for the analyses.

Land use variables

The Land Use Index (LUI, Eq. 1, adapted from Rawer-Jost et al. 2004) were calculated for the upstream catchment.

$$\text{LUI} = 4 \times \% \text{CAT}_{\text{urb}} + 2 \times \% \text{CAT}_{\text{agr}} + \% \text{CAT}_{\text{mod}} \text{ (Eq. 1)}$$

Where LUI is the Land Use Index; CAT_urb, CAT_agr and CAT_mod are, respectively, the percentage of urban, agricultural and pasture, and other uses (allotment, exposed soil, eucalyptus plantations) in the upstream catchment.

Tropical Water Health Index

To assess the influence of stream condition on leaf litter decomposition, the Tropical Water Health Index (TWHI) was used. The index was constructed using three components—pressure (alterations in land use), condition (hydrology, water quality, biological assemblages and ecosystem processes), and response (water body class)—which together represent overall ecosystem health. The index assigns each stream a value ranging from 0 to 1, with values closer to 1 indicating conditions more similar to the natural state (Campos et al., 2024).

Data Analysis

To investigate the relationships between leaf litter decomposition and environmental gradients, Generalized Additive Models (GAMs) were fitted, with decomposition rate constant (k) used as the response variable. Separate models were constructed to evaluate the relationship between decomposition and stream health index (TWHI), land use intensity index (LUI), and each land-use component within the upstream catchment, including natural vegetation, agriculture, urbanization, and other anthropogenic modifications. Generalized Additive Models (GAMs) were also used to evaluate variation in the density of EPT individuals (individuals g^{-1} remaining leaf litter) along the TWHI gradient. This approach allowed the identification of non-linear patterns and potential changes in response trends along the gradients.

To identify which limnological variables influence leaf litter decomposition, the Boosted Regression Trees (BRT) technique was applied. Decomposition (k multiplied by 1000) was used as the response variable, and explanatory variables included water temperature, conductivity, current velocity, turbidity, pH, dissolved oxygen, nitrate, and phosphate. Models were fitted assuming a Gaussian distribution, with tree complexity set to 5, learning rate of 0.01, and a bag fraction of 0.75. The relative importance of each variable was obtained from its percentage contribution to the model, and the relationships between the most influential variables and decomposition were evaluated using partial dependence plots.

A Principal Component Analysis (PCA) was performed using limnological variables to visualize multivariate structure and stream ordination in the space defined by the main axes. Sampling sites were color-coded according to TWHI intervals, allowing the identification of associations between decomposition, limnological conditions, and different levels of environmental integrity. Multiple linear regression was used to assess the relationship between leaf litter decomposition and microbial variables (ergosterol and ATP). All analyses were performed using R version 4.4.0 (R Core Team, 2024).

Results

Sensitivity of leaf litter decomposition to stream health gradient (TWHI) and land use

Leaf litter decomposition varied along the stream health gradient ($p < 0.001$), with the TWHI explaining approximately 21% of the observed variation ($R^2 = 0.21$). The pattern described by the model indicated a non-linear response: the lowest decomposition rates occurred in streams with both low and high TWHI values, whereas the highest rates were recorded in streams with intermediate levels of integrity. The model also showed that decomposition in coarse-mesh litterbags tended to be higher than in fine-mesh litterbags (Fig. 2A).

Decomposition was affected by land use intensity (LUI; $p < 0.001$; adjusted $R^2 = 0.18$). The response pattern was non-linear, indicating that decomposition did not change in a strictly increasing or decreasing manner along the LUI gradient. The fitted curve showed that decomposition was highest at intermediate levels of land use intensity, with lower rates at both extremes of the gradient (Fig. 2B).

Each specific land-use component exhibited distinct effects on leaf litter decomposition. Agricultural land use showed a significant effect on decomposition ($p < 0.001$), explaining 13.3% of the variation and representing one of the land-use components with the highest explanatory power when analyzed independently (Fig. 2D). Urbanization explained 4.93% of the variation ($p < 0.001$), with the fitted curve indicating an increase in decomposition even at low levels of urbanization (Fig. 2E). Other anthropogenic modifications within the watershed explained 2.43% of the variation in decomposition ($p < 0.001$) (Fig. 2F). Decomposition was also modulated by the percentage of natural area ($p < 0.001$), explaining 14.1% of the variation, a value similar to that observed for agricultural land use, indicating that natural land cover is a relatively strong isolated predictor (Fig. 2C). The distribution of points and the fitted GAM curve exhibited a pattern opposite to that observed for LUI, reflecting the inverse relationship between these two land-use metrics.

Responses of leaf litter decomposition to water physicochemical variables

The relative importance of the variables indicated that electrical conductivity was the main predictor in the model (31.9%), followed by temperature (24.5%) and turbidity (18.5%) (Fig. 3). The remaining variables showed smaller effects: nitrate (9.6%), dissolved oxygen (5.0%), water velocity (4.8%), pH (2.9%), and phosphate (2.4%). The BRT model explained 90.7% of the variation in decomposition.

Grouping of Streams Based on Limnological Variables

The Principal Component Analysis (PCA) based on limnological variables (Fig. 4) explained 51.9% of the total variation along the first two axes (PC1 = 33.6%; PC2 = 18.3%). Streams classified as optimal (blue) clustered on the right side of the ordination and were associated with higher dissolved oxygen values, in contrast to the vectors representing temperature, electrical conductivity, and nutrients. In contrast, poor-quality streams clustered toward the end of the ordination associated with higher values of these variables. Streams classified as good and moderate occupied intermediate positions, reflecting environmental conditions characterized by moderate values of these parameters.

Responses of leaf litter decomposition to biotic factors

EPT abundance showed a significant non-linear relationship with the stream health gradient (adjusted $R^2 = 0.13$; $p = 0.001$), following a unimodal pattern, with higher abundance at intermediate TWHI values (Fig. 5).

The relative abundance of each Order differed across the stream health gradient. Individuals of the Order *Plecoptera* were present only in streams classified as Very good. *Trichoptera* and *Ephemeroptera* were present in streams classified as Very good, Good, and Fair, with *Ephemeroptera* showing higher abundance in Fair streams. None of these orders were recorded in streams classified as Poor.

Fungal biomass, estimated by ergosterol concentration, showed a positive relationship with decomposition, being a significant predictor in the analysis ($p = 0.001$; Fig. 6A). Total microbial activity (ATP) was not significantly associated with decomposition ($p = 0.611$; Fig. 6B). Together, these variables explained 22% of the variation in decomposition rates ($R^2 = 0.22$; adjusted $R^2 = 0.18$; $p = 0.004$). The relationship between the stream health index (TWHI) and ergosterol and ATP was not significant ($p = 0.468$ and 0.209 , respectively).

Discussion

The results reveal that leaf litter decomposition in tropical streams does not decline monotonically with increasing anthropogenic disturbance, but instead exhibits a non-linear, unimodal response along continuous gradients of environmental integrity. This pattern indicates that ecosystem functioning emerges from the balance between resource-driven stimulation and biodiversity-mediated constraints, whereby moderate levels of disturbance enhance decomposition through increased nutrient availability and microbial activity, while higher levels of degradation lead to functional collapse due to habitat simplification and loss of sensitive taxa. Such dynamics are consistent with conceptual frameworks that predict non-linear ecosystem responses under multiple interacting stressors, including the intermediate disturbance hypothesis and the subsidy-stress gradient, but remain rarely demonstrated empirically at landscape scales in tropical systems (Townsend et al., 2008; Tonkin et al., 2013; Feld et al., 2011). By explicitly linking decomposition rates to continuous metrics of stream health and land use, this study advances a process-based perspective in freshwater ecology, showing that functional indicators can reveal emergent ecosystem properties that are not captured by traditional structural assessments, and highlighting the need to incorporate non-linear responses into biomonitoring and management frameworks (Allan, 2004; Gessner et al., 2010; Tiegs et al., 2019).

Non-linear ecosystem responses along gradients of environmental integrity

Our results demonstrate that leaf litter decomposition in tropical streams does not follow a linear decline with increasing anthropogenic disturbance, but instead exhibits a unimodal response along gradients of

environmental integrity and land use (Campos et al., 2024; Rawer-Jost et al., 2004; Yang et al., 2024). This pattern indicates that ecosystem functioning is structured by the interaction between environmental drivers and biological components, rather than responding monotonically to disturbance (Allan, 2004; Feld et al., 2011; Townsend et al., 2008). The peak in decomposition at intermediate levels of disturbance may reflect a balance between processes that stimulate organic matter processing, such as nutrient enrichment and increased metabolic activity, and processes that constrain it, including habitat degradation and loss of sensitive taxa (Ferreira et al., 2015; Tonkin et al., 2013; Tian and Yin, 2022). Although such non-linear responses are predicted by ecological theory, empirical evidence in tropical streams remains limited, particularly at landscape scales (Feld et al., 2011; Tiegs et al., 2019).

Land use gradients and functional trade-offs

The consistent unimodal response observed across both TWHI and LUI indicates that land use exerts non-linear effects on ecosystem functioning (Mosquera et al., 2026). The increase in decomposition under intermediate levels of agricultural influence aligns with evidence that moderate nutrient enrichment can enhance microbial activity and accelerate litter breakdown (Ferreira et al., 2015; Mancuso et al., 2023). However, this positive effect is not sustained at higher levels of disturbance, where decomposition declines, indicating that excessive land-use intensity imposes constraints on biological communities and ecosystem processes (Silva-Araujo et al., 2020; García et al., 2025; Pérez et al., 2023).

Urbanization exhibited a similar pattern, with increased decomposition at low levels of impact, which may be associated with changes in resource availability or nutrient inputs (Ferreira et al., 2015; Dong et al., 2025). The reduction in decomposition rates at higher levels of disturbance is consistent with studies showing that urban streams exhibit altered ecosystem functioning due to changes in water quality and habitat structure (Martins et al., 2015; Gao et al., 2022; Bohus et al., 2023). These results reinforce that land use promotes transitions between phases of functional stimulation and ecological limitation, rather than producing uniform responses across disturbance gradients (Allan, 2004; Yang et al., 2024).

Biological mediation and the role of macroinvertebrates

Biological patterns observed along the environmental gradient indicate that macroinvertebrates play a central role in mediating decomposition dynamics (Graça et al., 2015; Oester et al., 2023). The occurrence of Ephemeroptera and Trichoptera across a range of environmental conditions suggests greater tolerance to moderate disturbance, whereas Plecoptera were restricted to high-integrity streams, reflecting well-established sensitivity gradients among aquatic insects (Nessimian et al., 2008; Faria et al., 2021).

The absence of EPT taxa in highly degraded streams coincided with reduced decomposition rates, indicating that the loss of functionally important groups can lead to declines in ecosystem functioning (Lima et al., 2022; Brito et al., 2020). Conversely, higher abundances of these taxa at intermediate levels of disturbance were associated with increased decomposition, suggesting that community reorganization and the persistence of more tolerant taxa may contribute to enhanced processing rates

(Bonada et al., 2006; Oester et al., 2023; Barasa et al., 2025). These findings highlight that ecosystem functioning is strongly mediated by biological assemblages, and that shifts in community composition along environmental gradients directly influence organic matter processing (Tiegs et al., 2019; García et al., 2025).

Physicochemical controls of decomposition

Physicochemical variables played a key role in regulating decomposition, with temperature and electrical conductivity emerging as the most important predictors. The positive relationship with temperature is consistent with its effects on metabolic rates and the acceleration of microbial decomposition processes (Ferreira & Chauvet, 2011; Wilmot et al., 2021). Similarly, electrical conductivity, often associated with nutrient availability, was positively related to decomposition, suggesting that nutrient enrichment can stimulate microbial growth and activity (Ferreira et al., 2015; Dong et al, 2025).

In contrast, turbidity was negatively associated with decomposition, indicating that sediment inputs and associated habitat degradation may constrain organic matter processing. Increased turbidity is commonly linked to land-use impacts such as erosion and runoff, which alter habitat conditions and reduce the efficiency of decomposer communities (Fierro et al., 2017; Wen et al., 2017).

Microbial contributions and temporal constraints

The positive relationship between fungal biomass and decomposition confirms the central role of fungi in organic matter processing (Abelho et al., 2005; Baudy et al., 2021). Although bacterial activity was not significantly related to decomposition, bacteria may still exert a complementary role in the breakdown process (Pascoal & Cássio, 2004). However, the lack of significant relationships between microbial metrics and the environmental gradient indicates that microbial responses were not directly aligned with TWHI.

This apparent decoupling may be explained by methodological limitations, as ergosterol and ATP represent instantaneous measurements that do not capture temporal dynamics or successional changes in microbial communities during decomposition (Gessner & Chauvet, 1993; Graça et al., 2015). Microbial communities undergo successional shifts over time, and different environmental conditions may lead to distinct trajectories that influence decomposition rates but are not detectable through single-time sampling (Ferreira & Chauvet, 2011; Gessner et al., 2010). Therefore, temporal variability in microbial activity likely represents an important, but under-sampled, component of ecosystem functioning.

Integrating structure, function, and environmental gradients

Overall, our results demonstrate that leaf litter decomposition in tropical streams is governed by the interaction of landscape-scale pressures, local environmental conditions, and the structure of the biological community (Allan, 2004; Feld et al., 2011). The consistent detection of non-linear responses

across multiple environmental descriptors indicates that ecosystem functioning cannot be adequately described by linear models or inferred solely from structural indicators (Young et al., 2008; Tiegs et al., 2019).

Instead, decomposition reflects emergent properties arising from the interplay between environmental enrichment, habitat degradation, and community composition. The peak in decomposition at intermediate disturbance levels highlights that ecosystem functioning is maximized under conditions where resource availability is enhanced without substantial loss of biological integrity (Ferreira et al., 2015; Tonkin et al., 2013; Tian and Yin, 2022). These findings reinforce the importance of incorporating functional indicators and gradient-based approaches into biomonitoring frameworks, particularly in tropical systems where multiple stressors interact to shape ecosystem responses (Campos et al., 2024; Feld et al., 2011).

Conclusion

This study demonstrates that leaf litter decomposition in tropical streams responds non-linearly to gradients of environmental integrity and land use, with peak processing rates occurring at intermediate levels of disturbance. This unimodal pattern reflects the balance between nutrient-driven stimulation of microbial and detritivore activity and the negative effects of habitat degradation and biodiversity loss under high disturbance. Our findings show that ecosystem functioning is jointly regulated by landscape-scale pressures, local physicochemical conditions, and the structure of the biological community; macroinvertebrates, particularly EPT taxa, play a key role in mediating functional responses.

The decoupling observed between microbial metrics and environmental gradients highlights the limitations of snapshot measurements in capturing dynamic processes such as decomposition, emphasizing the need for temporally explicit approaches. Overall, the results reinforce that functional processes provide complementary and often more integrative information than traditional structural indicators. By revealing non-linear responses and potential thresholds along disturbance gradients, this study supports the incorporation of functional metrics into biomonitoring frameworks and contributes to improving the assessment and management of tropical freshwater ecosystems under increasing anthropogenic pressure.

Declarations

Author Contribution

M.S.A. wrote the manuscript, performed the statistical analyses, interpreted the results, and sorted and identified the macroinvertebrates. G.S. contributed to field sampling, data collection, and manuscript writing. R.R. contributed to the statistical analyses and critically revised the manuscript. C.A.C. contributed to the conceptual framework, methodology, field sampling, data collection, statistical analyses, and manuscript writing. J.F.G.J. conceived the study, developed the conceptual framework,

designed the methodology, formulated the hypotheses, interpreted the results, and supervised the project. All authors read, revised, and approved the final version of the manuscript.

Acknowledgement

The first author acknowledges the scholarship provided by the Coordination for the Improvement of Higher Education Personnel (CAPES). This study was financially supported by the Foundation for Research Support of the Federal District (FAP-DF; Call 05/2016 – Águas, Grant No. 193.000716/2016), which enabled the fieldwork and laboratory analyses. We also acknowledge the National Council for Scientific and Technological Development (CNPq) for the research fellowships awarded to José Francisco Gonçalves Júnior (Grant Nos. 310641/2017-9 and 311232/2021-3). RSR is grateful to National Council for Scientific and Technological Development (CNPq; No 302044/2022–1) and Foundation to Support the Research and Innovation of State of Santa Catarina (2024TR002336 and 2024TR2013). We greatly appreciate the collaboration of all students of the Aquariparia Limnology Laboratory, University of Brasília (UnB), for their assistance with fieldwork and laboratory analyses.

Data Availability

The dataset generated during the current study has been deposited in Figshare and is available to editors and reviewers during peer review through the following private link:

<https://figshare.com/s/991213fb4bff17bba2d1> . Upon acceptance of the manuscript, the dataset will be made publicly available through Figshare with a permanent DOI.

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Figures

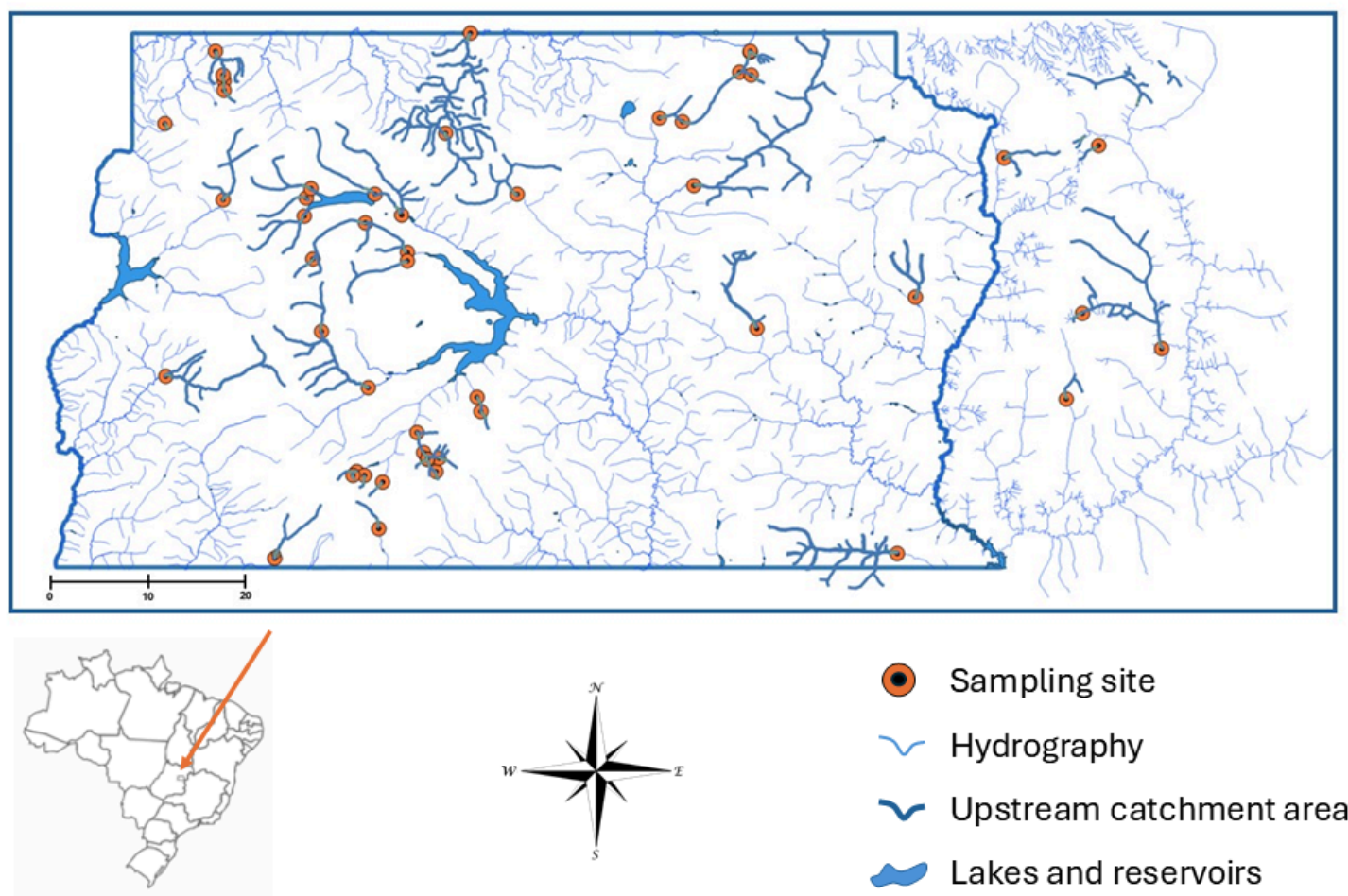


Figure 1

Study area showing the distribution of sampling sites. Adapted from Campos (2021).

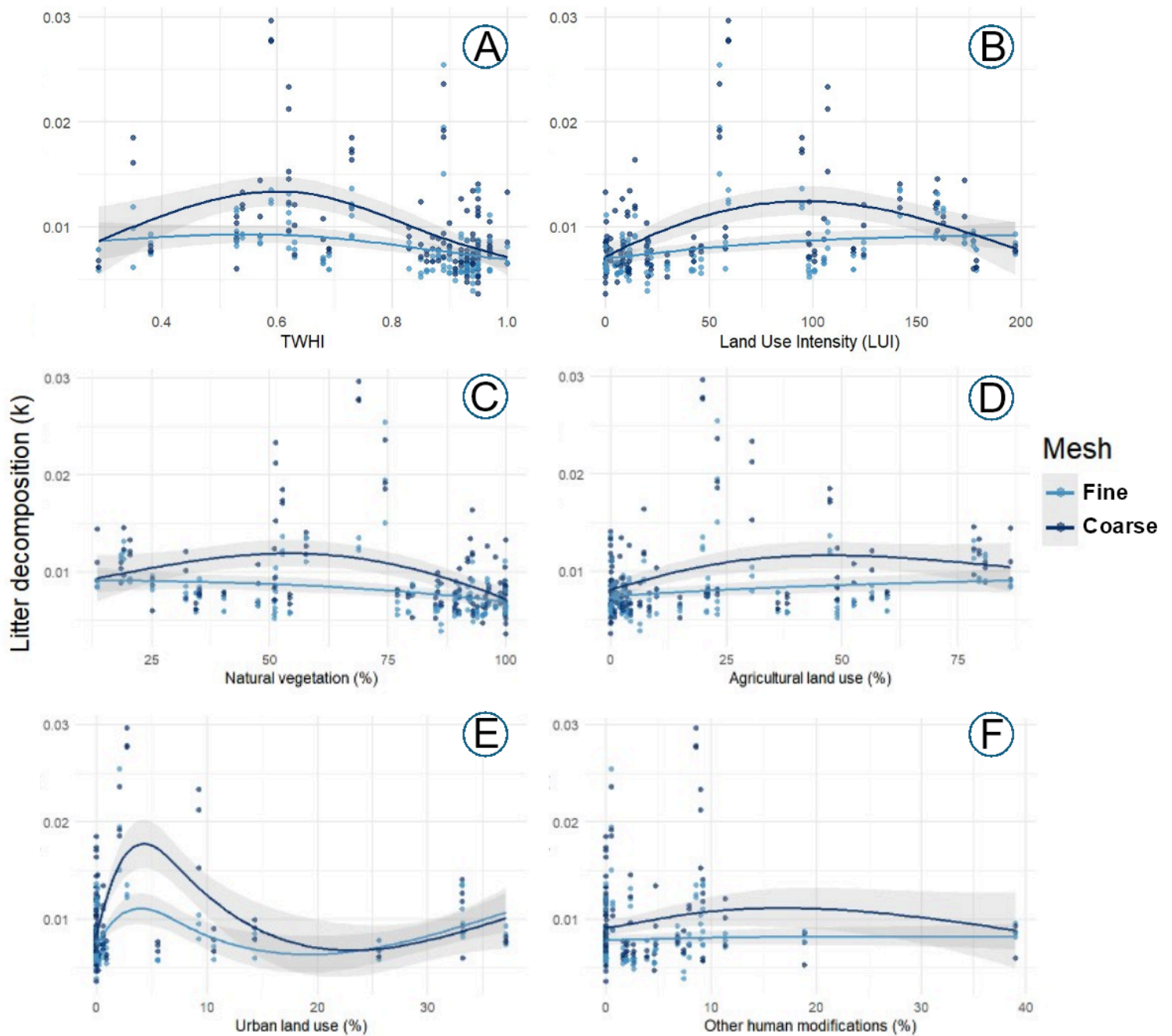


Figure 2

GAM models showing the relationship between decomposition and disturbance and land-use metrics: (A) stream health index (TWHI); (B) land use intensity index (LUI); (C) percentage of natural vegetation in the watershed; (D) percentage of agricultural area; (E) percentage of urbanization; and (F) other anthropogenic modifications. Curves represent the smoothed effect of each predictor on decomposition, while points illustrate the observed data dispersion.

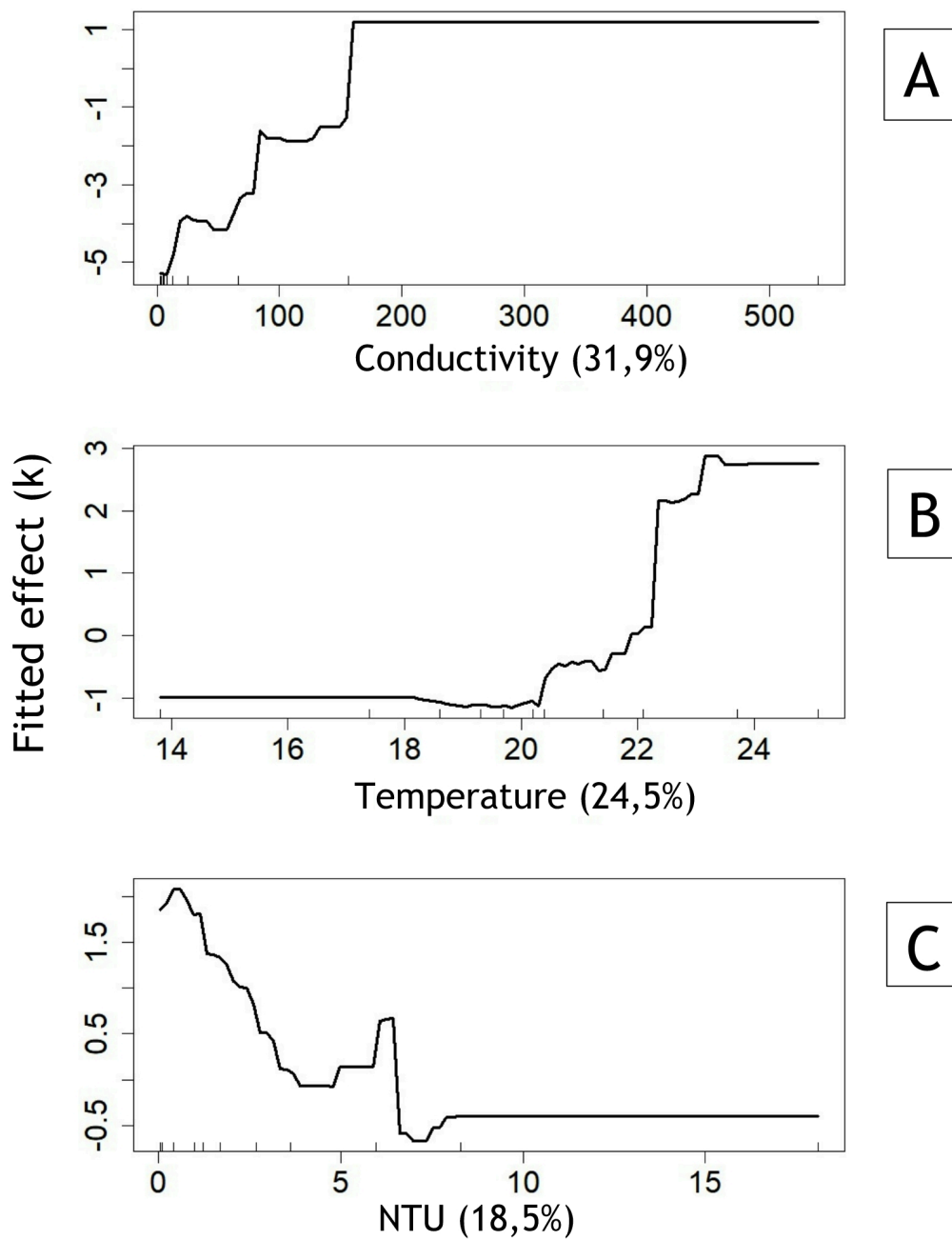


Figure 3

Boosted Regression Tree (BRT) model plots for the three most important variables. Electrical conductivity explained 31.9% of the variation in decomposition, followed by temperature (24.5%) and turbidity (18.5%).

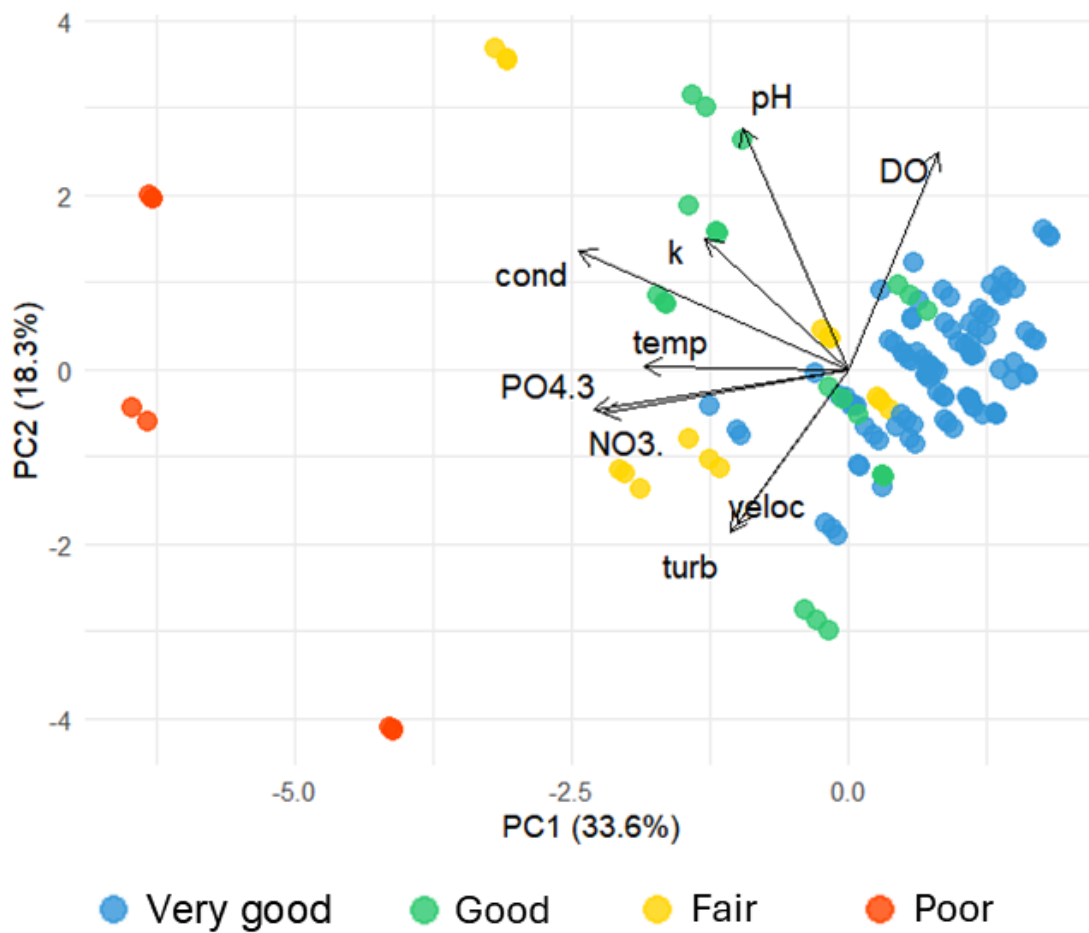


Figure 4

Principal Component Analysis (PCA) showing the ordination of sampling sites in relation to limnological variables. Sampling sites are classified according to Tropical Water Health Index (TWHI) intervals: Very good (0.81–1.0), Good (0.61–0.80), Fair (0.41–0.60), and Poor (0.21–0.40).

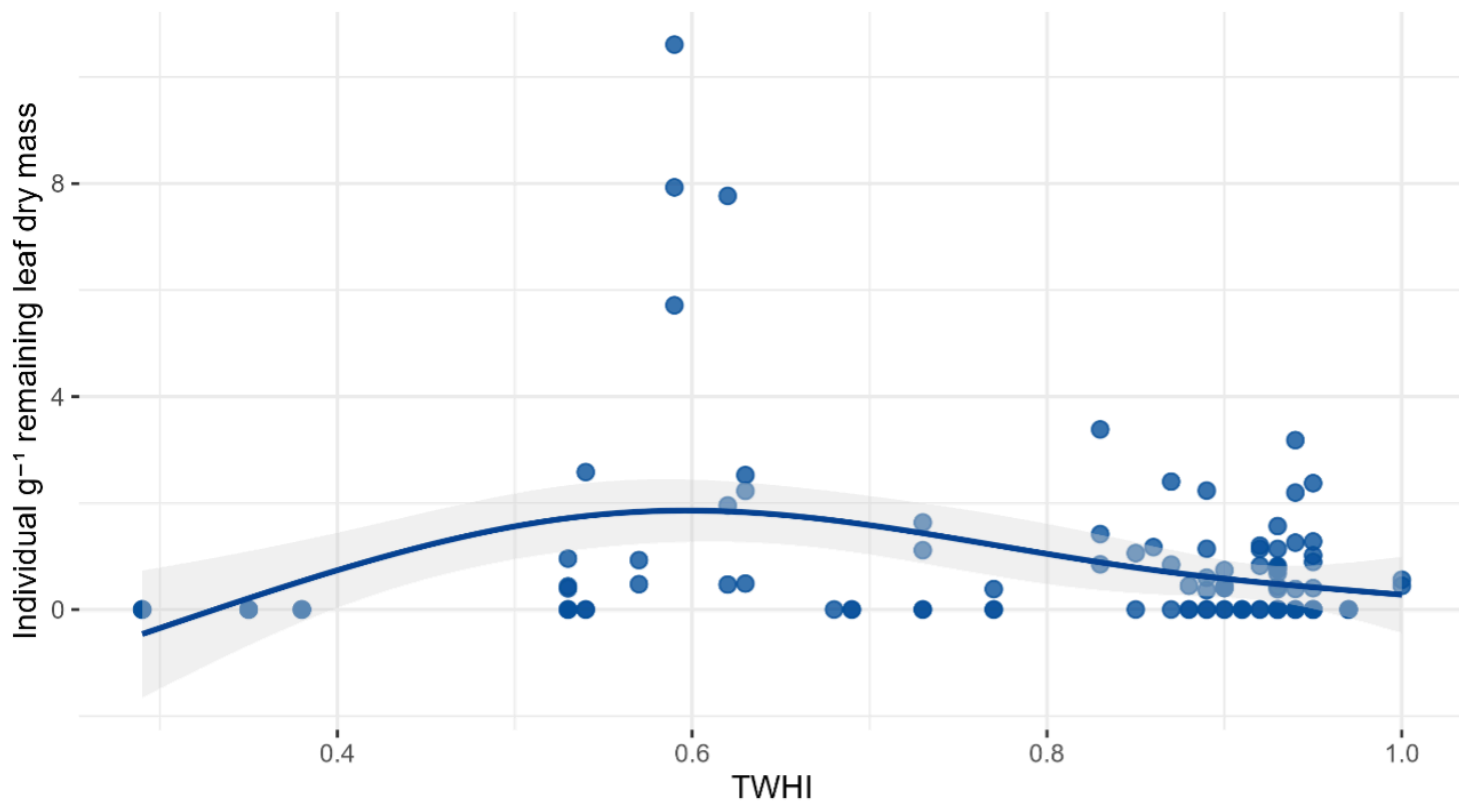


Figure 5

Generalized Additive Models showing the relationship between EPT abundance and TWHI.

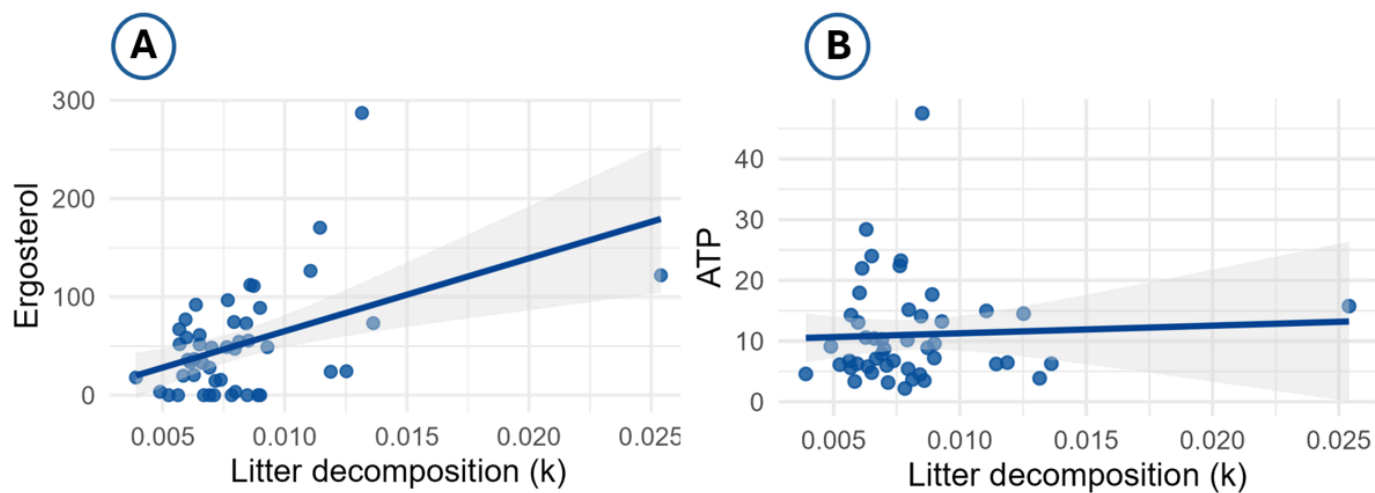


Figure 6

Relationship between leaf litter decomposition (k) and microbial descriptors. Panel (A) shows the relationship between decomposition (k) and ergosterol, while panel (B) shows the relationship between decomposition (k) and ATP.

