

Functional responses of benthic macroinvertebrate communities to rural-urban land-use gradients in Neotropical lowland streams

Respuesta funcional de las comunidades de macroinvertebrados bentónicos a gradientes de uso del suelo rural-urbano en arroyos neotropicales de llanura

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Abstract

In the province of Entre Ríos (Argentina), streams are increasingly affected by land-use change, including livestock production, urban expansion, and wastewater discharge, which generate multiple stressors such as pollution, sedimentation, hydromorphological alteration, and habitat degradation. This study assessed benthic macroinvertebrate communities in eight streams exposed to contrasting land uses in a Neotropical lowland region of Entre Ríos. Between 2013 and 2019, streams were sampled using a standardized multi-habitat protocol. Community structure, functional feeding groups (FFGs), and ecosystem attributes were analyzed using univariate and multivariate approaches. A total of 64 taxa were recorded, with lower richness in urban streams. Shredders were absent from urban streams and scarce overall. Urban streams also exhibited reduced abundance, functional diversity, and ecosystem attributes. These results indicate that urbanization negatively affects both community structure and ecosystem functioning. Integrating taxonomic and functional approaches can improve ecological assessments and support conservation and management of freshwater ecosystems under anthropogenic pressure.

Keywords: benthic macroinvertebrates, land-use change, urban streams, functional feeding groups, ecosystem functioning, freshwater bioassessment.

Resumen

En la provincia de Entre Ríos (Argentina), los arroyos se encuentran cada vez más afectados por cambios en el uso del suelo. Este fenómeno incluye la producción ganadera, la expansión urbana y las descargas de aguas residuales, que generan múltiples estresores como la contaminación, la sedimentación, las alteraciones hidromorfológicas y la degradación del hábitat. Este estudio evaluó las comunidades de macroinvertebrados bentónicos en ocho arroyos expuestos a usos del suelo contrastantes en una región neotropical de llanura de Entre Ríos. Entre 2013 y 2019, se muestrearon los arroyos mediante un protocolo estandarizado para múltiples hábitats. La estructura de las comunidades, los grupos funcionales tróficos (GFT) y los atributos ecosistémicos fueron analizados mediante enfoques univariados y multivariados. Se registraron 64 taxones, con menor riqueza en los arroyos urbanos. Los fragmentadores estuvieron ausentes en los arroyos urbanos y fueron escasos en general. Asimismo, los arroyos urbanos presentaron menor abundancia, diversidad funcional y atributos ecosistémicos. Estos resultados indican que la urbanización afecta negativamente tanto la estructura de las comunidades como el funcionamiento de los ecosistemas. La integración de enfoques taxonómicos y funcionales puede mejorar las evaluaciones ecológicas y contribuir a la conservación y gestión de los ecosistemas de agua dulce sometidos a presión antrópica.

Palabras clave: macroinvertebrados bentónicos, cambio de uso del suelo, arroyos urbanos, grupos funcionales tróficos, funcionamiento ecosistémico, bioevaluación de ecosistemas dulceacuícolas.

Introduction

Human-induced alteration of freshwater ecosystems is an increasingly important global concern because it affects not only water quality and quantity but also the ecological integrity of aquatic habitats. Surface waters are particularly vulnerable to multiple anthropogenic stressors associated with land-use change, including pollution, sedimentation, and hydromorphological alterations (UNEP 2002; Srebotnjak et al., 2012; Frau et al., 2019; Ríos-Touma & Ramírez, 2019). These stressors arise from activities such as dam construction, agricultural and livestock production, wetland loss, urban expansion, nutrient enrichment, and the discharge of contaminants, including heavy metals, pesticides, industrial effluents, and emerging contaminants (Allan, 2004; Elosegui & Sabater, 2009; Berger et al., 2017; Juárez et al., 2018).

In rural landscapes, environmental degradation is primarily associated with agricultural and livestock activities that increase sediment loads, nutrient inputs, pesticide runoff, and changes in stream morphology (Rodrigues Capítulo et al., 2010; Menezes et al., 2019; Paredes del Puerto et al., 2021). Urban streams, in contrast, are typically exposed to multiple concurrent stressors, including domestic wastewater, stormwater

runoff, industrial discharges, impervious surface expansion, and channel alteration (Berger et al., 2017; Tagliaferro et al., 2019; Paz et al., 2022). Collectively, these pressures can modify community composition and disproportionately affect environmentally sensitive taxa (Domínguez et al., 2022).

Benthic macroinvertebrates are widely used in freshwater biomonitoring because of their high taxonomic and functional diversity, relative ease of sampling, and sensitivity to environmental change (Barbour et al., 1999; Friberg et al., 2011; Menezes et al., 2019). As key components of aquatic food webs, they mediate the transfer of energy and matter between basal resources and higher trophic levels (Allan & Castillo, 2007; Burwood et al., 2021). Their classification into functional feeding groups (FFGs) according to feeding strategy and resource use (Merritt & Cummins, 1996; Cummins & Klug, 1979) provides a useful framework for evaluating energy pathways, organic matter processing, and ecosystem functioning (Velásquez & Miserendino, 2003; Cummins et al., 2005, 2016).

Accordingly, FFG-based metrics have been increasingly incorporated into stream assessments to characterize ecological conditions and infer ecosystem attributes, including the balance between gross primary production and community respiration (P/R) and the dynamics of

coarse and fine particulate organic matter (CPOM, FPOM) transport and retention (Merritt et al., 2002; Cummins et al., 2005). These functional approaches complement taxonomic analyses by providing information on ecological processes that may not be evident from community composition alone.

Land-use change frequently alters the composition and relative abundance of FFGs. Agricultural and urban intensification are generally associated with reductions in functional diversity and shifts in group representation, whereas streams with well-preserved riparian vegetation tend to support greater abundances of scrapers, predators, and collector-gatherers (Lammert & Allan, 1999; Bruno et al., 2014; Miserendino et al., 2011; Fierro et al., 2017). Consequently, benthic macroinvertebrate communities constitute effective indicators of environmental disturbance at both local and catchment scales (Burwood et al., 2021; Fierro et al., 2017).

In Argentina, studies using aquatic bioindicators have expanded considerably, particularly in the Pampas region, where the abundance of freshwater ecosystems coincides with intense agricultural, urban, and industrial pressures (Domínguez et al., 2022; Amuchástegui et al., 2016; Tagliaferro et al., 2019). Within this region, the province of Entre Ríos contains more than 7,000 water bodies, including streams, wetlands, and ravines that provide essential ecosystem services to rural and urban populations (Crettaz-Minaglia et al., 2018; Luiz et al., 1998). In urban areas, streams supply water for human use, receive wastewater inputs, and support recreational activities, whereas in rural landscapes they contribute to irrigation, livestock production, and the conservation of natural environments (Crettaz-Minaglia & Juárez, 2020).

These streams are embedded within interconnected fluvial networks in which upstream and downstream processes influence hydrological and ecological dynamics across the landscape, consistent with the principles of the River Continuum Concept (Vannote et al., 1980). Understanding how land use affects both taxonomic and functional attributes of aquatic communities is therefore essential for assessing ecosystem condition and supporting freshwater management.

In this context, the present study evaluated the taxonomic and functional structure of benthic

macroinvertebrate communities, as well as associated ecosystem attributes, in streams subjected to contrasting land uses (urban and rural) within a Neotropical sector of the province of Entre Ríos, Argentina. We tested the hypotheses that: a) the taxonomic and functional structure of benthic macroinvertebrate communities differs between rural and urban streams; and b) these differences are associated with variation in sediment characteristics related to land use.

Materials and methods

Study area

The study was conducted in the lower basin of the Gualeguaychú River, located in southeastern Entre Ríos Province, Argentina, within the Neotropical biogeographic region (Arana et al., 2017). The Gualeguaychú River basin drains approximately 6,690 km² and extends for about 250 km, originating in the Colón Department and flowing into the Uruguay River in the Gualeguaychú Department. Its hydrological regime is influenced by regional precipitation patterns and local flooding dynamics, whereas the natural vegetation is characterized by mixed riparian forests and hydrophilic plant communities along stream margins.

Eight streams distributed throughout the lower basin were selected to represent rural and urban environments exposed to different disturbance regimes (Figure 1; Table 2). Four streams were classified as urban based on their proximity to the city of Gualeguaychú: El Zapallo Stream (EZS), El Mangrullo Stream (EMS), La Capilla Stream (LCAS), and El Cura Stream (ECS), the latter of which is located at the urban fringe. According to local land-use classifications, these sites are situated within “green areas”, urban sectors with limited infrastructure development that include recreational spaces, remnant native vegetation, and low-intensity land uses.

EZS and EMS flow through the Unzué Multipurpose Park, a recreational area frequently visited by residents and tourists, where alterations to stream banks, flow conditions, and waste accumulation have been documented (Crettaz-Minaglia et al., 2019). Despite habitat fragmentation, the area includes the Parque Florístico nature reserve, which supports native flora and associated fauna. ECS and LCAS are affected by runoff

from agricultural and livestock activities, subsistence hunting, solid waste disposal, and channel modifications. In addition, ECS receives treated domestic effluent from the municipal wastewater treatment plant (Ávila-Hernández et al., 2019). The coordinates of the sampling sites are shown in Table 1.

The rural streams—Santa Bárbara (SBS), Los Perros (LPS), La Cañana (LCS), and García (GAS)—are located outside municipal boundaries. These watersheds are

characterized by mixed production systems (Juárez et al., 2016), dominated by soybean cultivation, followed by wheat, sorghum, and corn in rotation, together with extensive cattle grazing (Crettaz-Minaglia et al., 2014). Livestock production is primarily based on cattle raised under extensive fattening systems (1–7 animals ha⁻¹), with pasture supplemented by grain and silage. Water for livestock consumption is obtained directly from the streams (Juárez et al., 2018).

Figure 1. Geographic location of the study area in the lower Gualeguaychú River basin, Entre Ríos Province, Argentina. The left panels show the location of the Gualeguaychú River basin within the province of Entre Ríos, Argentina, and the position of the study area within the basin. The right panel shows the distribution of the eight sampled streams: Los Perros (LPS), Santa Bárbara (SBS), La Cañada (LCS), García (GAS), El Cura (ECS), La Capilla (LCAS), El Mangrullo (EMS), and El Zapallo (EZS). Rural streams correspond to LPS, SBS, LCS, and GAS, whereas urban streams correspond to ECS, LCAS, EMS, and EZS.

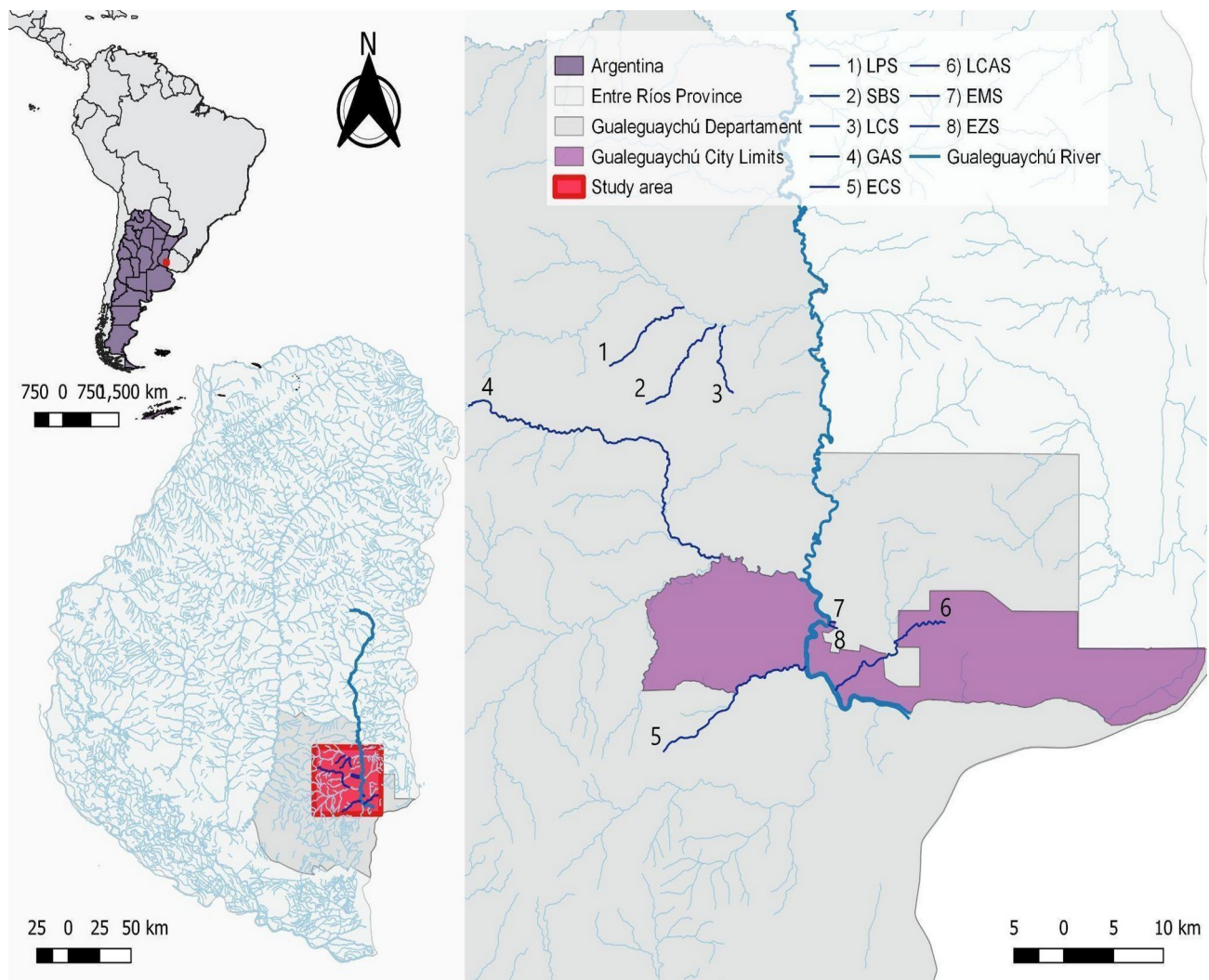


Table 1. Geographic coordinates of the eight study streams. Rural streams: SBS, LPS, LCS and GAS; urban streams: ECS, LCAS, EZS and EMS.

Stream	Code	Latitude (°)	Longitude (°)
Santa Bárbara	SBS	−32.80330	−58.61790
Los Perros	LPS	−32.76987	−58.63912
La Cañada	LCS	−32.81330	−58.59304
García	GAS	−32.94694	−58.61781
El Cura	ECS	−33.05100	−58.55580
La Capilla	LCAS	−33.02740	−58.42790
El Zapallo	EZS	−33.00999	−58.48671
El Mangrullo	EMS	−33.00683	−58.48497

Sampling points and frequency

One sampling point (SP) was established in each stream. Sampling dates were selected to coincide with periods when macroinvertebrates were expected to be fully developed but prior to adult emergence, following the recommendations of [Lunde and Resh \(2012\)](#). All surveys were conducted under baseflow conditions, avoiding flood or post-flood periods to minimize hydrological variability among sampling events.

Sampling was conducted between autumn and early spring, excluding winter and summer because extreme temperatures and periods of intense rainfall may reduce macroinvertebrate activity and compromise seasonal comparability among streams and years. Samples were collected during 2013 ($n = 1$), 2014–2015 ($n = 3$), 2016–2017 ($n = 1$), and 2018–2019 ($n = 3$), where n represents the number of streams sampled during each period.

At each SP, three benthic samples and one integrated sediment sample were collected from the main channel, including both margins. The total number of sampling events per stream ranged from two to four and was determined using taxon accumulation curves to ensure that at least 90% of the estimated richness was represented. Accumulation curves were generated

by sequentially adding sampling events until an asymptotic or near-asymptotic pattern was achieved.

Benthic macroinvertebrates

Benthic macroinvertebrates were collected using a standardized multi-habitat sampling approach ([Lunde & Resh, 2012](#)). At each SP, three sediment samples were obtained from the channel center and both margins using an Ekman dredge (225 cm²) and a hand net with a mesh size of 250 µm. Samples were preserved in the field with 4% formaldehyde until laboratory processing.

In the laboratory, samples were washed through a 250 µm sieve with pressurized tap water and stained with Erythrosin B to facilitate organism detection. Macroinvertebrates were sorted under a Motic stereomicroscope at 10× and 30× magnification and identified to the lowest possible taxonomic level using available taxonomic keys ([Domínguez & Fernández, 2009](#)). All specimens were preserved and deposited in the collection of the Laboratorio de Indicadores Biológicos y Gestión Ambiental de Calidad de Agua (IBGA Lab) at the Universidad Autónoma de Entre Ríos, Argentina.

Functional feeding groups

Macroinvertebrates were assigned to five functional feeding groups (FFGs): shredders (Sh), filtering collectors (FC), gathering collectors (GC), scrapers (S), and predators (P), following Cummins et al. (2005), Rodríguez-Barrios et al. (2011), and Andramunio-Acero and Caraballo (2012). The classification of taxa and associated food resources is presented in Table 3.

The following ecosystem attributes were estimated using FFG composition according to Cummins et al. (2005):

Autotrophy/Heterotrophy Index (P/R). Calculated as the ratio of scrapers plus shredders and total collectors ($SHR + FC / GC + FC$). Values > 0.75 indicate a predominance of autotrophic conditions.

CPOM/FPOM ratio. Indicates riparian contribution and resource availability for shredders. It was calculated as $Sh / (Sh + FC + GC)$. Values > 0.25 suggest a well-functioning riparian zone.

FPOM Index (TFPOM/BFPOM). Estimates the relative importance of suspended versus benthic fine particulate organic matter using the FC/GC ratio. Values > 0.50 indicate elevated transport of suspended FPOM.

Substratum stability index. Calculated as: $(Sh + FC) / (S + GC)$. Values > 0.50 indicate relatively stable substrates, such as cobbles, woody debris, or rooted vegetation.

Sediments

Sediment types were qualitatively characterized by measuring randomly selected substrate particles with a Vernier caliper, following the methodology of Juárez et al. (2016). Mineral particles were classified into size classes following Gayraud & Philippe (2003), whereas boulders, bedrock and organic matter were defined according to Barbour et al. (1999). The sediment categories used in this study are summarized in Table 4.

Data analysis

Field and laboratory data were organized and analyzed using RStudio version 1.3.1093 running under Ubuntu 20.04.4 LTS (R Core Team, 2020), following the analytical framework proposed by Palacio et al. (2020).

Analyses were designed to evaluate differences in taxonomic composition, community structure, and functional attributes between rural and urban streams in accordance with the study hypotheses.

For each stream, total richness, total abundance, and abundance per sample were calculated. Community structure was assessed through hierarchical clustering based on macroinvertebrate abundance standardized by sampled area (individuals m^{-2}), using Manhattan distance and the Ward.D2 agglomerative method. The sampled area for each stream was estimated from the effective area covered by the hand net during the standardized sampling procedure, considering net width and sampling distance.

Cluster analyses were performed using the R packages *cluster* (Maechler et al., 2021) and *dendextend* (Galili, 2015). Non-metric multidimensional scaling (NMDS) was conducted with the *vegan* package (Oksanen et al., 2020) to visualize patterns of community differentiation between rural and urban streams. Multiple Correspondence Analysis (MCA) was applied using *FactoMineR* (Husson et al., 2016) to explore associations between macroinvertebrate families and sediment categories, thereby evaluating relationships between community composition and substrate characteristics.

All graphical outputs were generated using *ggplot2* (Wickham, 2016). Data normality was assessed with the Shapiro–Wilk test. Because assumptions of normality were not met, differences between rural and urban streams were evaluated using Kruskal–Wallis tests followed by Bonferroni-adjusted post hoc comparisons ($\alpha < 0.05$). Pairwise comparisons were conducted using the Mann–Whitney U test in the *MultNonParam* package (Jankowski, 2021; Gianello et al., 2019).

Results

A total of 72 taxa were recorded, belonging to four phyla: Arthropoda (58 taxa), Mollusca (11), Annelida (2), and Nematoda (1). Arthropoda dominated rural streams, with the families Caenidae and Chironomidae (Insecta) and Aeglidae (Malacostraca) contributing most to total abundance. In contrast, urban streams were characterized by the predominance of molluscan

taxa, particularly the gastropod families Planorbidae, Cochliopidae, and Ampullariidae, and the bivalve families Sphaeriidae and Corbiculidae.

Taxonomic richness was consistently higher in rural streams (21–53 taxa) than in urban streams (9–15 taxa) (Figure 2A; Table 5). Conversely, macroinvertebrate density, expressed as individuals per square meter (ind m^{-2}), was substantially greater in urban streams (1,881–11,156 ind m^{-2}) than in rural streams (11–114 ind m^{-2}) (Figure 2B; Table 5).

Sediment composition differed markedly among streams (Table 3). The SBS, LPS, and LCS streams were characterized by sand, clay, and organic matter at different stages of decomposition, whereas LCS additionally contained gravel. GAS differed from the remaining rural streams by presenting predominantly coarse substrates, including boulders, pebbles, and gravel, with no detectable organic matter. Urban streams were dominated by fine-texture substrates, mainly clayey silt, with low organic matter content. LCAS contained sand deposits, and a substantial portion of its channel bed was covered by hardened concrete associated with road and bridge infrastructure.

The NMDS ordination (Figure 3) showed a separation in community composition between rural and urban streams, supported by a significant PERMANOVA result ($R^2 = 0.255$, $F = 12.68$, $p = 0.001$; stress = 0.16). Land use explained 25.5% of the variability in community composition. Rural sites tended to show greater dispersion in ordination space, whereas urban streams appeared to form a more compact cluster with substantial overlap, although differences in multivariate dispersion were not statistically significant (betadisper: $p = 0.146$). Within the rural group, GAS and LCS were positioned separately from LPS and SBS, whereas LPS and SBS largely overlapped, suggesting a similar assemblage structure. Most taxa were associated with rural sites, with only a few taxa positioned toward urban samples. Rural assemblages were characterized primarily by arthropods, whereas urban assemblages showed a greater relative representation of mollusks, annelids, and nematodes.

Five functional feeding groups (FFGs) were identified across the study streams; however, shredders were absent from all urban sites (Table 6). In SBS and LPS streams, gathering collectors dominated the assemblages, accounting for 76.1% and 80.6% of individuals, respectively, followed by scrapers (12.8% and 9.1%), filtering collectors (5.8% and 6.0%), shredders (6.2% and 2.3%), and predators (approximately 2% in both streams). In contrast, LCS was characterized by a high proportion of shredders (42.5%), followed by gathering collectors, predators, scrapers, and filtering collectors. GAS was dominated by filtering collectors (35.8%), with lower contributions from scrapers, gathering collectors, shredders, and predators. Urban streams were overwhelmingly dominated by gathering collectors (85.8%–94.8%), followed by filtering collectors and scrapers. Predators occurred at low relative abundances (< 5%), whereas shredders were not recorded (Table 6).

Statistical analyses indicated significant differences in FFG composition among streams ($p < 0.05$), with large effect sizes ($\eta^2 = 0.37$ – 0.76) and moderate statistical power of 0.76 (Table 6).

The autotrophy-heterotrophy index (P/R) indicated that all streams were heterotrophic ($P/R < 0.75$). No significant differences were detected among streams ($p > 0.05$), and the effect size was small ($\eta^2 = 0.057$), despite high statistical power (0.9835). The CPOM/FPOM ratio exceeded the threshold associated with well-functioning riparian zones (> 0.25) only in LCS and GAS. Significant differences were detected among streams ($p < 0.05$), with a large effect size ($\eta^2 = 0.2$) and high statistical power (0.9835). Significant pairwise differences were observed between SBS and EZS, and EMS, LCS and LCAS, EZS and EMS, and GAS and ECS, EZS and EMS.

The TFPOM/BFPOM ratio and the substrate stability index exceeded their respective threshold values (> 0.50) only in GAS, indicating greater transport of suspended fine particulate organic matter and relatively stable substrates. However, neither metric differed significantly among streams ($p > 0.05$). A detailed summary of all ecosystem attributes is provided in Table 7.

Discussion

This study evaluated whether the taxonomic and functional structure of benthic macroinvertebrate communities differs between rural and urban streams and whether these differences are associated with land-use-linked sediment characteristics. Overall, the results support both hypotheses. Rural and urban streams differed markedly in community composition, functional feeding group structure, and ecosystem attributes. Rural streams exhibited greater taxonomic richness and a more balanced functional organization, whereas urban streams were characterized by lower richness and assemblages dominated by a limited number of tolerant taxa and functional groups. These patterns were associated with contrasting substrate conditions, with rural streams generally exhibiting greater habitat heterogeneity and greater availability of coarse substrates and organic resources, whereas urban streams were dominated by fine sediments and had reduced habitat complexity. Together, these findings suggest that land-use-related alterations in habitat characteristics influence both the structure and functional organization of benthic macroinvertebrate communities in lowland streams.

Most studies conducted in South American freshwater ecosystems have focused on biological assemblages as indicators of water quality or anthropogenic disturbance using conventional metrics such as richness, abundance, diversity, and the occurrence of tolerant taxa (Cretazz-Minaglia et al., 2014; Juárez et al., 2016; Tomanova & Tedesco, 2007; Tomanova et al., 2008; Juárez et al., 2018; Gianello et al., 2019). Although these metrics are valuable for detecting ecological change, they provide limited information about ecosystem processes and functional organization (Juárez et al., 2018). This is an important limitation, as many of the effects of anthropogenic stressors on freshwater ecosystems are expressed not only through changes in species composition, but also through emergent properties; i.e., the interactions among community components and their environment, and the ecosystem services and functions they support. Embracing these broader ecological dimensions represents a shift toward a new paradigm in freshwater biomonitoring, one that builds on long-term

environmental studies to better understand functional integrity.

Macroinvertebrate richness and abundance showed contrasting patterns between land-use categories. Rural streams exhibited higher taxonomic richness but lower densities, whereas urban streams presented lower richness and markedly higher densities. Similar patterns have been reported in other Neotropical and temperate streams, where habitat simplification and environmental disturbance reduce taxonomic diversity while favoring the proliferation of a limited number of tolerant taxa (Hepp et al., 2010; Miserendino et al., 2011; Lundquist et al., 2019; Pereira et al., 2021; Suárez et al., 2022). The higher richness observed in rural streams is consistent with the greater habitat heterogeneity and availability of organic resources associated with more structured riparian environments (Suriano & Fonseca-Gessner, 2013).

Differences between rural and urban streams were also reflected in community composition. Rural assemblages were dominated by arthropods, whereas urban assemblages showed a greater relative contribution of mollusks, annelids and nematodes. The separation between stream categories, combined with the absence of statistically significant differences in multivariate dispersion, suggests that land use is associated with a shift in community composition rather than only with differences in within-group variability. Most taxa were associated with rural sites, and urban streams tended to form a more compact group, suggesting that urban streams support a reduced subset of tolerant taxa, consistent with a possible process of biological homogenization.

Functional analyses revealed that gathering collectors were the dominant FFG in most streams regardless of land use, reflecting the importance of fine particulate organic matter as a food resource in lowland systems. However, important differences emerged in the representation of other functional groups. Shredders were recorded exclusively in rural streams and reached their highest abundance in LCS, whereas filtering collectors dominated GAS. The occurrence of shredders in rural streams and their absence from urban streams are consistent with this group's dependence on riparian-derived coarse particulate organic matter and

relatively intact stream-riparian linkages (Juárez et al., 2016). Similar patterns have been reported by Peng et al. (2024), who observed lower abundance and occurrence of shredders in urbanized streams compared with collector groups, suggesting that their adaptability to urban environments is markedly lower.

Scrapers were also more abundant in rural streams, particularly in GAS, where coarse mineral substrates were more prevalent. Hard substrates provide suitable surfaces for the development of periphyton and biofilms that constitute the primary food resource for this functional group. Predators exhibited the lowest relative abundances across most streams, although their representation was comparatively higher in LCS. Because predators occupy upper trophic positions, their abundance is generally constrained by prey availability and energy transfer from lower trophic levels.

The predominance of gathering collectors in SBS and LPS is consistent with the substrate characteristics observed in these streams, where sand, silt, and decomposing organic matter provide conditions conducive to the accumulation of fine particulate organic matter. These organisms feed by ingesting sediments or collecting fine particles in depositional areas, relying on decomposing FPOM as a food source (Juárez et al., 2016). In urban streams, assemblages were largely dominated by gathering collectors, followed by filtering collectors and scrapers. These communities were composed mainly of taxa commonly associated with enriched sediments and altered environmental conditions, including Cochliopidae, Oligochaeta, and several bivalve taxa. The absence of shredders and the low abundance of predators in urban streams suggest a simplified trophic structure and reduced functional complexity.

The relationship between riparian condition and FFG composition is further supported by the results obtained for LCS, which exhibited the highest richness and the greatest relative abundance of shredders. Riparian vegetation constitutes a major source of allochthonous organic matter and plays a fundamental role in maintaining stream ecosystem functioning by regulating temperature, stabilizing banks, and retaining sediments and nutrients (Zhang et al., 2013).

Accordingly, Fierro et al. (2017) reported reductions in shredder abundance and increases in collector groups following the loss of native riparian vegetation, while Wang et al. (2012) documented declines in shredders, filtering collectors, and scrapers along urbanization gradients.

The ecosystem attributes derived from FFG composition provided additional insights into stream functioning. All streams were classified as heterotrophic based on the P/R index, indicating a predominance of respiration relative to primary production. This pattern is consistent with observations from other lowland streams (Pereira et al., 2021) and reflects the importance of allochthonous organic matter inputs in systems where primary production is relatively limited.

Among the ecosystem attributes evaluated, the CPOM/FPOM ratio was particularly informative. Values exceeding the threshold associated with well-functioning riparian zones were recorded only in LCS and GAS, where shredders were also present. These results reinforce the functional connection between riparian vegetation, coarse organic matter availability, and shredder communities. The significant differences observed among streams indicate that this metric is sensitive to land-use-related environmental changes and may be useful for assessing riparian integrity in lowland stream ecosystems.

The TFPOM/BFPOM ratio and substrate stability index identified GAS as functionally distinct from the remaining streams. This site exhibited the highest values for both metrics, consistent with the presence of coarse mineral substrates and greater substrate stability. In contrast, streams dominated by fine sediments exhibited lower values. This does not necessarily imply loss of functionality. Instead, it may reflect natural conditions of depositional environments typical of soft-bottom lowland streams, where organic matter accumulation and reduced flow are common. These findings underscore the importance of interpreting such indices within their geomorphological context to avoid overestimating degradation.

Benthic macroinvertebrates play a central role in aquatic food webs by linking basal resources with

higher trophic levels and mediating key ecosystem processes (Allan & Castillo, 2007). The patterns observed in this study demonstrate that changes in land use and substrate characteristics are reflected not only in taxonomic composition but also in the functional organization of stream communities. These relationships are particularly relevant in small lowland streams, which contribute energy, organic matter, and biota to larger fluvial systems. In this regard, the observed patterns are consistent with the River Continuum Concept (Vannote et al., 1980), emphasizing the importance of local habitat conditions in sustaining ecological processes across connected river networks.

Conclusions

Urban streams exhibited stronger signatures of anthropogenic disturbance than rural streams, as reflected in the taxonomic and functional characteristics of benthic macroinvertebrate communities. Urban sites were consistently characterized by lower taxonomic richness, higher organism densities, and a functional structure dominated by gathering collectors, followed by filtering collectors and scrapers, together with low proportions of predators and the absence of shredders. In contrast, rural streams generally supported higher taxonomic richness, greater functional diversity, and a more balanced representation of functional feeding groups.

The observed differences between stream types were associated with contrasting substrate conditions and riparian characteristics. Rural streams were generally characterized by greater habitat heterogeneity and the presence of coarse substrates and organic matter resources, whereas urban streams were dominated by fine sediments and reduced habitat complexity. These environmental differences were reflected not only in community composition but also in ecosystem attributes derived from functional feeding groups.

Our results suggest that urban-related stressors, including channel modification, riverbank alteration, and wastewater inputs, are associated with stronger changes in benthic community structure and functioning than those observed in streams primarily

affected by extensive agricultural and livestock activities. Consequently, urbanization processes lacking adequate environmental planning pose a serious threat to aquatic communities and stream conservation, ultimately compromising the ecological integrity of stream ecosystems and the services they provide to surrounding human populations.

This study demonstrates that land use influences both the taxonomic structure and the functional organization of macroinvertebrate assemblages in Neotropical lowland streams. Functional indicators based on feeding-group composition and ecosystem attributes provided complementary information to traditional taxonomic metrics and were effective in detecting ecological differences among streams subjected to contrasting land uses. Their incorporation into biomonitoring programs may therefore improve assessments of ecosystem condition and contribute to more comprehensive freshwater management strategies.

Finally, the conservation of stream ecosystems requires management approaches that integrate ecological functioning with conventional assessments of biological integrity. Strengthening collaboration among researchers, local stakeholders, and decision-makers will be essential for developing conservation and management policies capable of maintaining the ecological integrity and ecosystem services of freshwater environments under increasing land-use pressure.

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water quality using benthic macroinvertebrates (proposal): Res. C.S. 050/15, 2015]; and *Determinación de la calidad ambiental del arroyo El Cura (Gualeguaychú, Entre Ríos)* [Determination of the environmental quality of the El Cura stream (Gualeguaychú, Entre Ríos); Res. C.S./17, 2017]. UADER also provided individual research fellowships to MCCM (Res. C.S. UADER Nº 1006-12) and EAH (Res. C.S. UADER Nº 221/15). We are grateful to the students and faculty members of the Laboratorio de Indicadores Biológicos y Gestión Ambiental de Calidad de Agua (IBGA Laboratory) for their assistance with field sampling in streams of the lower Gualeguaychú River basin.

Author's contributions

MCCM: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Writing – original draft; Writing – review & editing. DG: Formal analysis; Investigation; Methodology; Validation; Visualization; Writing – original draft; Writing – review & editing. EAH: Formal analysis; Investigation; Writing – original draft; Writing – review & editing. EAC: Investigation; Resources; Supervision; Writing – original draft; Writing – review & editing. IA: Investigation; Funding acquisition; Project administration; Supervision; Writing – original draft; Writing – review & editing.

Figure 2. Variation in benthic macroinvertebrate taxonomic richness and density among the studied streams. **A)** Taxonomic richness (number of taxa). **B)** Macroinvertebrate density (ind. m⁻²). Blue boxplots correspond to rural streams and orange boxplots to urban streams. Distribution of benthic macroinvertebrates across the studied streams. Gray points represent individual sampling events; boxplots summarize the distribution of values for each stream.

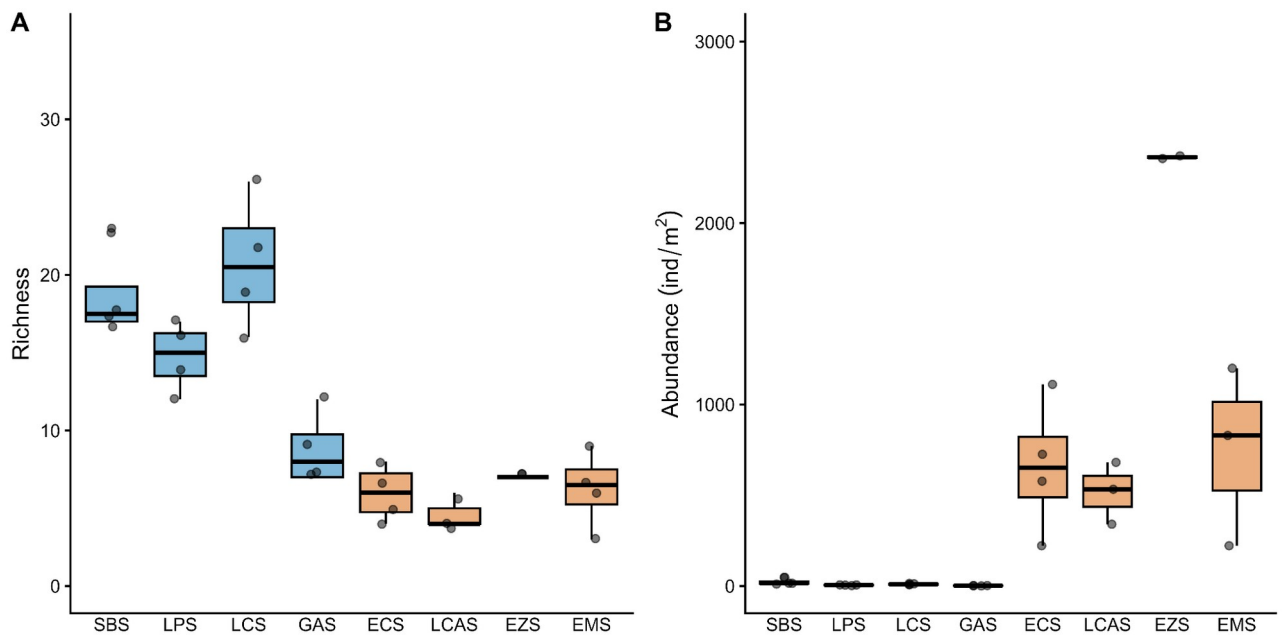


Figure 4. Multiple correspondence analysis (MCA) based on substrate types and functional feeding groups (FFGs) for each studied stream. Blue points represent rural streams (SBS= Santa Bárbara, LPS= Los Perros, LCS= La Cañada, GAS= García) and, orange points represent urban streams (ECS= El Cura, LCAS= La Capilla, EMS= El Mangrullo, EZS= El Zapallo); om = organic matter; sa = sand; silt = silt; g = gravel; s = stone; ss = small stone; sh = shingle; cl = clay; Sh = shredder; FC = filtering collector; GC = gathering collector; S = scraper; P = predator; _yes = presence; _no = absent.

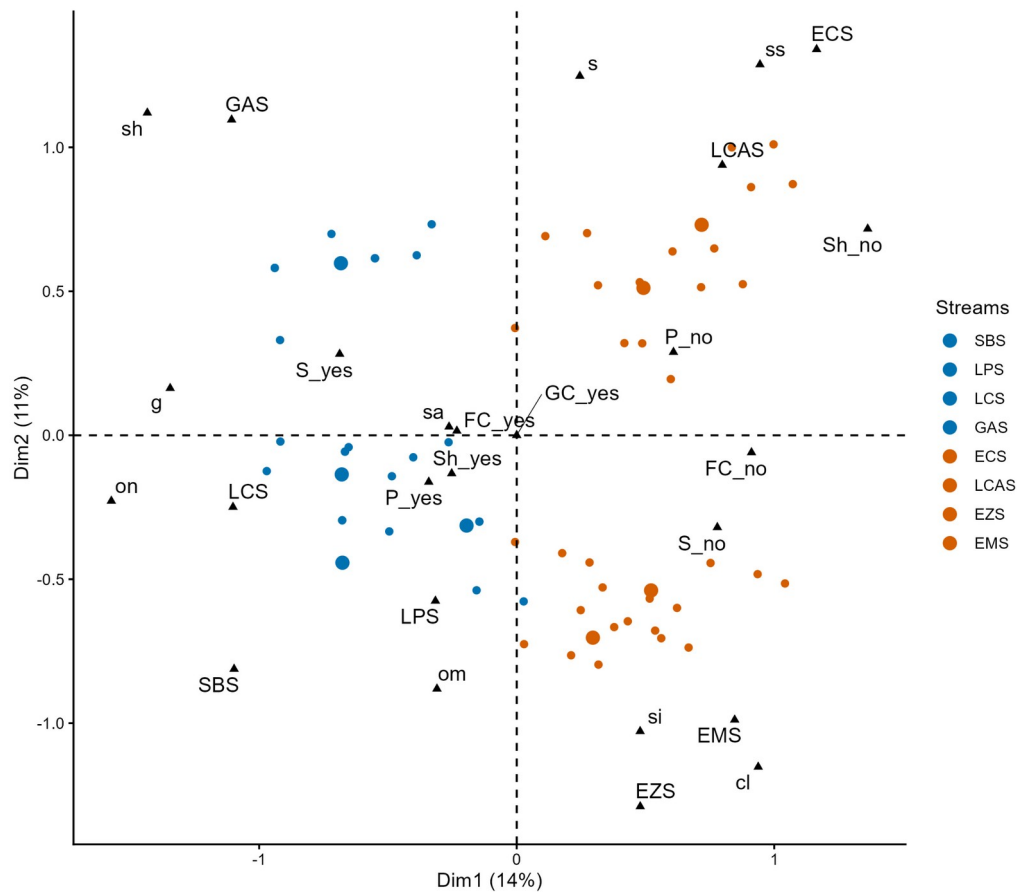


Table 2. Description of the studied streams in the lower basin of the Gualeguaychú River (Entre Ríos, Argentina). * Riverbank and flood valley.

Stream	Dominant land use and anthropogenic pressures	Land-use category	Stream order	Length (km)	Width * (m)	Depth (m)	Drainage area (km ²)	Flow (m ³ /s)	Sampling period	Sampling events	Ref.
SBS	Agriculture, livestock	Rural	2	8.2	4.9	0.33	41	0.30	2013	4	Juárez et al. (2018)
LPS	Livestock	Rural	1	9.6	7.6	0.63	20	0.12	2014-2015	4	Juárez et al. (2016)
LCS	Dairy farming, agriculture	Rural	2	5.2	1.6	0.22	18.6	0.00	2014-2015	4	Gianello et al. (2016); Juárez et al. (2016)
GAS	Unauthorized hunting, conservation area	Rural	2	36.5	4.6	0.42	308	1.04	2014-2015	4	Juárez et al. (2016)
ECS	Agriculture, livestock, solid waste disposal, unauthorized hunting	Urban	3	9.0	12.1	0.25	94.8	0.30	2016-2017	4	Ávila-Hernández et al. (2019)
LCAS	Recreational use	Urban	3	15.9	11.7	0.40	136	1.43	2018-2019	3	Crettaz-Minaglia et al. (2019)
EZS	Recreational use	Urban	1	0.76	3.5	0.47	0.13	0.00	2018-2019	2	Crettaz-Minaglia et al. (2019)
EMS	Recreational use	Urban	1	0.43	1.3	1.63	0.06	0.02	2018-2019	4	Crettaz-Minaglia et al. (2019)

Table 3. Functional feeding groups (FFGs) of benthic macroinvertebrates, feeding mechanisms, dominant food resources, and typical food particle size ranges. Adapted from Cummins et al., 2005.

Functional feeding groups	Feeding mechanism	Dominant food resources	Typical food particle size (mm)
Shredders	Chew conditioned leaf litter, living vascular plant tissue, or decaying wood	CPOM, including decomposing leaf litter and other vascular plants	> 1.0
Filtering collectors	Filter suspended particles from the water column	FPOM, including detrital particles, algae, bacteria, and fecal material	0.1–1.0
Gathering collectors	Collect or ingest deposited particles from sediments	FPOM, including detrital particles, algae, bacteria, and fecal material	0.05–1.0
Scrapers	Graze biofilms on rock, wood, and aquatic plant surfaces	Periphyton, attached algae, associated detritus, microorganisms, and fecal material	0.01–1.0
Predators	Capture and consume live animal prey or ingest animal tissues and body fluids	Living animal prey	> 0.5

Table 4. Substrate categories used for sediment characterization. Mineral substrates were classified by particle size following Gayraud & Philippe (2003); boulders (> 256 mm), bedrock and organic matter were defined according to Barbour et al. (1999).

Type of substrate	Particle size / description
Mineral substrates (particle size)	
Silt and clay	< 0.05 mm
Sand	0.05–2 mm
Gravel	2–16 mm
Pebbles	16–64 mm
Cobbles	64–256 mm
Boulders	> 256 mm
Other substrates (nature)	
Bedrock	Continuous rocky surface
Organic matter	Very fine organic matter

Table 5. Taxonomic richness and macroinvertebrate density recorded in rural and urban streams of the lower Gualeguaychú River basin.

Stream	Land-use category	Taxonomic richness (n)	Total density (ind. m ⁻²)	Total density per sampling event (ind. m ⁻²)
SBS	Rural	35	114	19
LPS	Rural	32	74	15
LCS	Rural	53	52	10
GAS	Rural	21	11	2
ECS	Urban	11	3274	546
LCAS	Urban	11	1881	376
EZS	Urban	9	4726	1575
EMS	Urban	15	11156	2231

Table 6. Percentage abundance of functional feeding groups (FFGs) in each studied stream. *Different letters indicate statistically significant differences between streams ($p < 0.05$). Sh = shredder; FC = filtering collector; GC = gathering collector; S = scraper; P = predator.

Stream	Land-use category	Sh (%)	FC (%)	GC (%)	S (%)	P (%)
SBS	Rural	6.2 ^{abcdefg}	5.8 ^{abc}	76.0 ^{abdef}	12.8 ^{abcde}	2.1 ^{abf}
LPS	Rural	2.3 ^{bh}	6.0 ^{ac}	80.6 ^{acdf}	9.4 ^{abcde}	2.1 ^{afb}
LCS	Rural	42.5 ^{hcddefg}	7.2 ^a	28.2 ^{bc}	10.8 ^{abcde}	11.2 ^{agbcde}
GAS	Rural	13.6 ^{c, d, e, f, g}	35.8 ^{b, d}	18.5 ^{c, a}	27.3 ^{a, b, c, d, e}	6.1 ^{a, b}
ECS	Urban	1.8 ^d	6.3 ^a	87.8 ^d	3.6 ^b	0.5 ^{b, d}
LCAS	Urban	4.7 ^e	3.2 ^{a, d}	85.8 ^e	3.9 ^c	2.4 ^c
EZS	Urban	0.0 ^f	8.2 ^a	86.2 ^a	3.8 ^d	1.9 ^d
EMS	Urban	0.0 ^f	2.7 ^c	94.8 ^f	2.0 ^e	0.5 ^e

Table 7. Median values of ecosystem attributes derived from benthic macroinvertebrate functional feeding groups in the studied streams. *Different letters indicate statistically significant differences between streams ($p < 0.05$).

Stream	Land-use category	P/R ratio	CPOM/FPOM ratio	TFPOM/BFPOM ratio	Substrate stability index
SBS	Rural	0.150 ^a	0.078 ^a	0.079 ^a	0.234 ^a
LPS	Rural	0.103 ^a	0.027 ^a	0.075 ^a	0.183 ^a
LCS	Rural	0.139 ^a	1.201 ^{ac}	0.255 ^a	0.255 ^a
GAS	Rural	0.402 ^a	0.251 ^{ad}	1.934 ^a	1.962 ^a
ECS	Urban	0.038 ^a	0.019 ^{ae}	0.072 ^a	0.111 ^a
LCAS	Urban	0.042 ^a	0.053 ^{bc}	0.037 ^a	0.078 ^a
EZS	Urban	0.040 ^a	0.000 ^{bce}	0.095 ^a	0.138 ^a
EZS	Urban	0.020 ^a	0.000 ^{bce}	0.028 ^a	0.049 ^a

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