Application of Zooplankton Indicators for Assessing Ecological Functioning Across an Urbanization Gradient

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Abstract: Urbanization is one of the most pervasive drivers of freshwater ecosystem degradation, altering hydrology, nutrient loading, and habitat structure in ponds, lakes, and reservoirs embedded within growing metropolitan landscapes. Zooplankton communities, owing to their short generation times, sensitivity to water-quality change, and central position in pelagic food webs, are increasingly recognized as effective bioindicators of ecological functioning. This study examined zooplankton assemblages across eight standing-water sites distributed along a rural-to-highly-urban gradient, quantified by percentage impervious surface cover in the surrounding catchment (4-81%). Zooplankton density, taxa richness, Shannon-Wiener diversity (H'), Pielou evenness (J'), and the rotifer-to-crustacean abundance ratio were used as indicators of ecological condition, alongside supporting water-quality variables (total phosphorus and chlorophyll-a). Diversity and richness declined sharply and significantly with increasing imperviousness ($r = -0.94$ and -0.97, respectively; $p < 0.001$), while the rotifer-to-crustacean ratio increased more than five-fold from rural to highly urban sites ($r = 0.96$, $p < 0.001$), reflecting a shift toward small, tolerant taxa under nutrient enrichment and hydrological instability. Zooplankton density exhibited a unimodal response, peaking at intermediate urbanization before declining in the most impervious catchments, consistent with a subsidy-stress model in which moderate nutrient enrichment initially increases secondary production before habitat degradation suppresses it. These results support the use of zooplankton community metrics, and in particular the rotifer:crustacean ratio and Shannon diversity index, as sensitive and cost-effective indicators for urban water-body monitoring programs and management decision-making.

Keywords: zooplankton, bioindicators, urbanization gradient, freshwater ecology, Shannon diversity, rotifer-crustacean ratio, urban stream syndrome

1. Introduction

Global urban land cover has expanded rapidly over the past four decades, and this expansion is projected to continue as an increasing proportion of the world's population concentrates in cities. Urban development fundamentally reorganizes the hydrology, geomorphology, and biogeochemistry of freshwater systems embedded within cityscapes, producing a suite of characteristic degradations frequently described as the 'urban stream syndrome.' Impervious surfaces such as roads, rooftops, and parking areas increase surface runoff, elevate peak discharge, deliver higher loads of nutrients, sediments, and contaminants, and reduce the buffering capacity that vegetated catchments normally provide. Standing water bodies embedded in urban and peri-urban landscapes, including retention ponds, urban lakes, and reservoirs, are particularly susceptible to these cumulative pressures because they act as terminal sinks for catchment-derived nutrients and pollutants.

Assessing the ecological condition of these water bodies requires indicators that respond predictably and rapidly to changing environmental conditions. Zooplankton, comprising rotifers, cladocerans, and copepods, are widely regarded as valuable bioindicators for several reasons. Their short life cycles and rapid reproductive rates allow them to respond to environmental change over days to weeks, in contrast to fish or macrophyte communities that integrate change over much longer time scales. Zooplankton also occupy a central trophic position, linking primary producers (phytoplankton) to higher consumers (planktivorous fish and macroinvertebrates), so that shifts in zooplankton community structure often cascade through the food web and reflect broader ecosystem functioning. Furthermore, different zooplankton taxa exhibit differential sensitivity to eutrophication, hydrological disturbance, and toxicant exposure: cladocerans and calanoid copepods are generally associated with clearer, less disturbed conditions, whereas small-bodied rotifers and cyclopoid copepods tend to dominate under nutrient-enriched, physically unstable, or predation-release conditions typical of urban water bodies.

Despite this recognized potential, relatively few studies have systematically quantified zooplankton community responses across a continuous, well-characterized urbanization gradient using standardized sampling and a consistent suite of ecological indices. The present study addresses this gap by examining zooplankton density, diversity, evenness, taxonomic composition, and the rotifer-to-crustacean ratio across eight lentic sites spanning rural to highly urbanized catchments. We hypothesized that (i) zooplankton diversity and richness would decline monotonically with increasing catchment imperviousness; (ii) the relative abundance of rotifers would increase at the expense of crustacean zooplankton along the same gradient; and (iii) zooplankton density would follow a unimodal, subsidy-stress pattern, initially increasing with moderate nutrient enrichment before declining under severe urban stress. The objective of this research is to evaluate the utility of zooplankton-based metrics as practical indicators of ecological functioning for use in urban water-resource monitoring and management programs.

2. Materials and Methods

2.1 Study Area and Site Selection

Eight lentic water bodies (ponds and small reservoirs of comparable surface area, 0.8-2.4 ha, and mean depth, 1.5-3.0 m) were selected to represent a continuous gradient of catchment urbanization. Catchment land use was quantified using geospatial land-cover classification, and percentage impervious surface cover within a 500 m buffer of each water body was used as the primary quantitative index of urbanization intensity, ranging from 4% at the least disturbed rural site to 81% at the most heavily urbanized site. Sites were grouped into four qualitative categories for interpretive purposes: Rural (0-10% impervious cover), Peri-urban (10-35%), Urban (35-65%), and Highly Urban (65-100%), with two replicate sites sampled within each category (Table 1).

2.2 Zooplankton Sampling and Identification

Zooplankton were sampled monthly over a six-month period (dry-to-wet transitional season) using vertical net hauls (64 µm mesh, 30 cm diameter) taken from the deepest point of each water body, with three replicate hauls composited per site per sampling date. Samples were preserved in 4% buffered formalin and enumerated under a stereomicroscope using a Sedgewick-Rafter counting chamber. Organisms were identified to the lowest practicable taxonomic level (typically genus or species) using standard regional taxonomic keys for Rotifera, Cladocera, and Copepoda. Zooplankton density was expressed as individuals per litre (ind. L^{-1}), and relative abundance was calculated for each of the three major taxonomic groups.

2.3 Ecological Indices

Four community-level indices were calculated for each site from mean seasonal abundance data: (i) taxa richness (S), the total number of taxa recorded; (ii) the Shannon-Wiener diversity index ($H' = -\Sigma p_i \ln p_i$, where p_i is the proportional abundance of taxon i); (iii) Pielou's evenness ($J' = H'/\ln S$); and (iv) the rotifer-to-crustacean abundance ratio (sum of rotifer abundance divided by the sum of cladoceran and copepod abundance), which has been used previously as an indicator of trophic state and physical disturbance because rotifers tend to be more tolerant of eutrophic and physically unstable conditions than most crustacean zooplankton.

2.4 Supporting Water-Quality Variables

Total phosphorus and chlorophyll-a concentrations were measured concurrently with zooplankton sampling using standard spectrophotometric methods, to provide independent confirmation of the trophic gradient associated with catchment urbanization and to contextualize zooplankton community responses.

2.5 Statistical Analysis

Relationships between percentage impervious surface cover and each zooplankton metric were assessed using Pearson product-moment correlation. Because zooplankton density was hypothesized to show a non-monotonic (unimodal) response, a second-order polynomial regression was additionally fitted to the density data. Significance was assessed at $\alpha = 0.05$. All analyses were performed using standard statistical computing software.

3. Results

3.1 Site Characteristics

The eight study sites captured a wide and approximately continuous gradient of catchment imperviousness (4-81%), accompanied by a corresponding increase in total phosphorus (12.4-97.3 µg L^{-1}) and chlorophyll-a concentration (3.1-36.9 µg L^{-1}), confirming that the physical urbanization gradient was closely coupled to a trophic-state gradient (Table 1).

Table 1. Site characteristics along the rural-to-urban gradient, including catchment land use, percentage impervious surface cover, and concurrent water-quality variables.

Site Code	Category	Land-Use Description	Impervious Surface (%)	Total Phosphorus (µg L^{-1})	Chlorophyll-a (µg L^{-1})
R1	Rural	Forested / low-density agriculture	4	12.4	3.1
R2	Rural	Pasture, riparian buffer intact	7	15.8	4.0
PU1	Peri-urban	Mixed residential–agricultural fringe	22	28.3	8.7
PU2	Peri-urban	Low-density suburban development	28	33.6	10.2
U1	Urban	Residential/commercial, stormwater inputs	48	54.2	17.5
U2	Urban	Dense residential, channelized inflow	55	61.0	20.4
HU1	Highly Urban	Central business district runoff	74	88.7	31.6
HU2	Highly Urban	Industrial/impervious catchment	81	97.3	36.9

3.2 Zooplankton Density and Diversity

Zooplankton density ranged from 46.5 to 67.2 ind. L^{-1} across sites and displayed a unimodal pattern along the urbanization gradient, increasing from rural to urban sites before declining at the two highly urban sites (Table 2; Figure 3). Taxa richness declined steadily and substantially from 22-24 taxa at rural sites to only 7-9 taxa at highly urban sites. The Shannon-Wiener diversity index followed the same monotonic declining trend, falling from a mean of 2.77 at rural sites to 1.00 at highly urban sites (Table 2; Figure 1), and Pielou's evenness declined in parallel from approximately 0.89 to 0.48, indicating that highly urban assemblages were not only less rich but also more strongly dominated by a small number of taxa.

Table 2. Zooplankton density and diversity indices at each of the eight sampling sites.

Site	Density (ind. L^{-1})	Taxa Richness (S)	Shannon H'	Pielou Evenness (J')	Rotifer:Crustacean Ratio
R1	52.5	24	2.89	0.91	0.86
R2	53.2	22	2.65	0.86	0.93
PU1	57.5	19	2.35	0.80	1.63
PU2	61.7	18	2.24	0.78	1.63
U1	67.2	14	1.68	0.64	3.01
U2	63.2	13	1.59	0.62	3.10
HU1	55.9	9	1.15	0.52	3.87
HU2	46.5	7	0.85	0.44	4.55

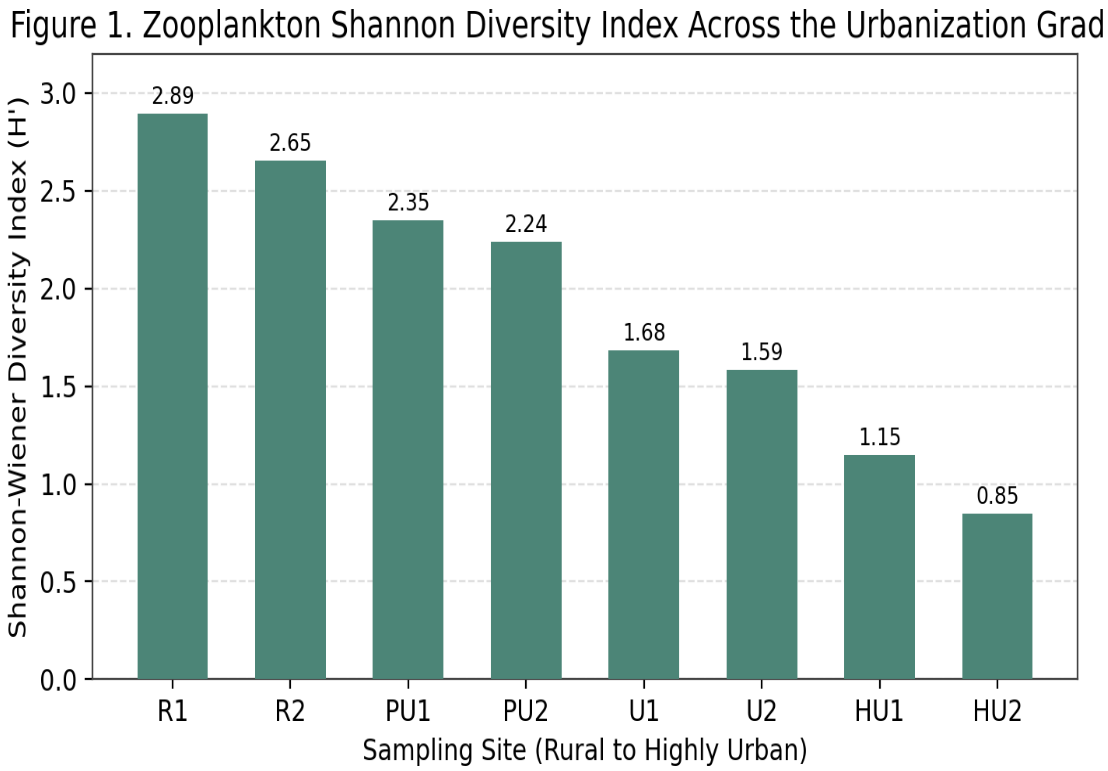

Figure 1. Zooplankton Shannon-Wiener diversity index (H') declines progressively from rural to highly urban sites.

3.3 Community Composition

Taxonomic composition shifted markedly along the urbanization gradient (Figure 2). Rotifera comprised approximately 31% of total zooplankton abundance at rural sites, increasing to approximately 73% at highly urban sites, while the combined relative abundance of Cladocera and Copepoda declined correspondingly. This compositional shift is quantitatively captured by the rotifer-to-crustacean ratio, which increased more than five-fold, from a mean of 0.90 at rural sites to 4.21 at highly urban sites (Table 2; Figure 4), reflecting a clear transition toward small-bodied, rapidly reproducing, and more tolerant taxa under conditions of higher nutrient loading and greater hydrological instability.

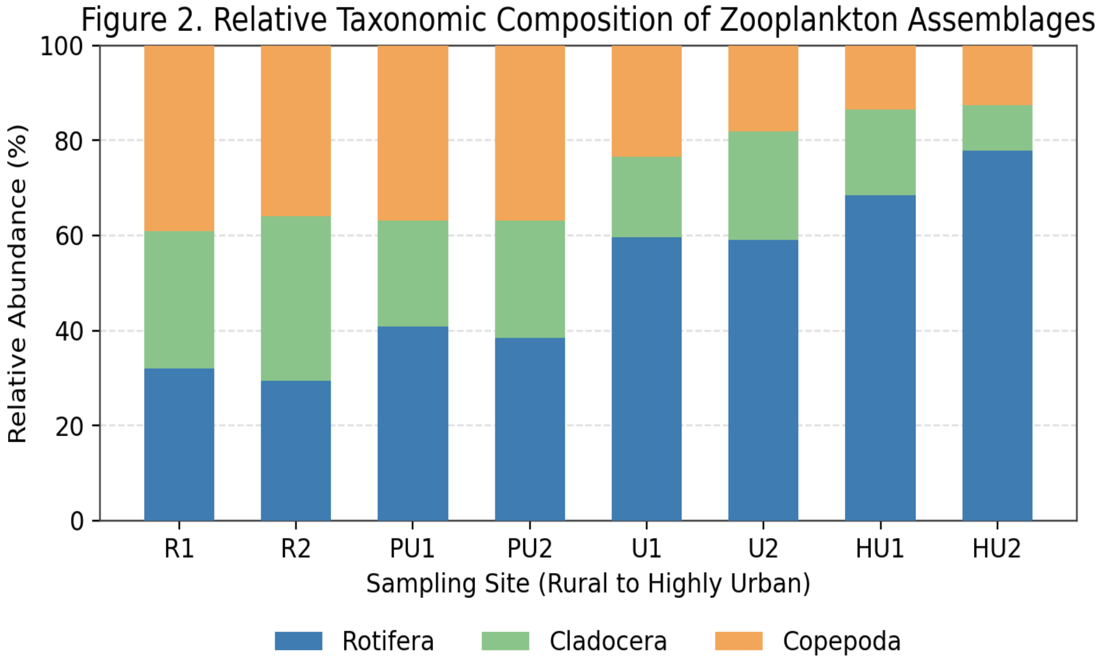

Figure 2. Relative taxonomic composition (Rotifera, Cladocera, Copepoda) of zooplankton assemblages across the urbanization gradient.

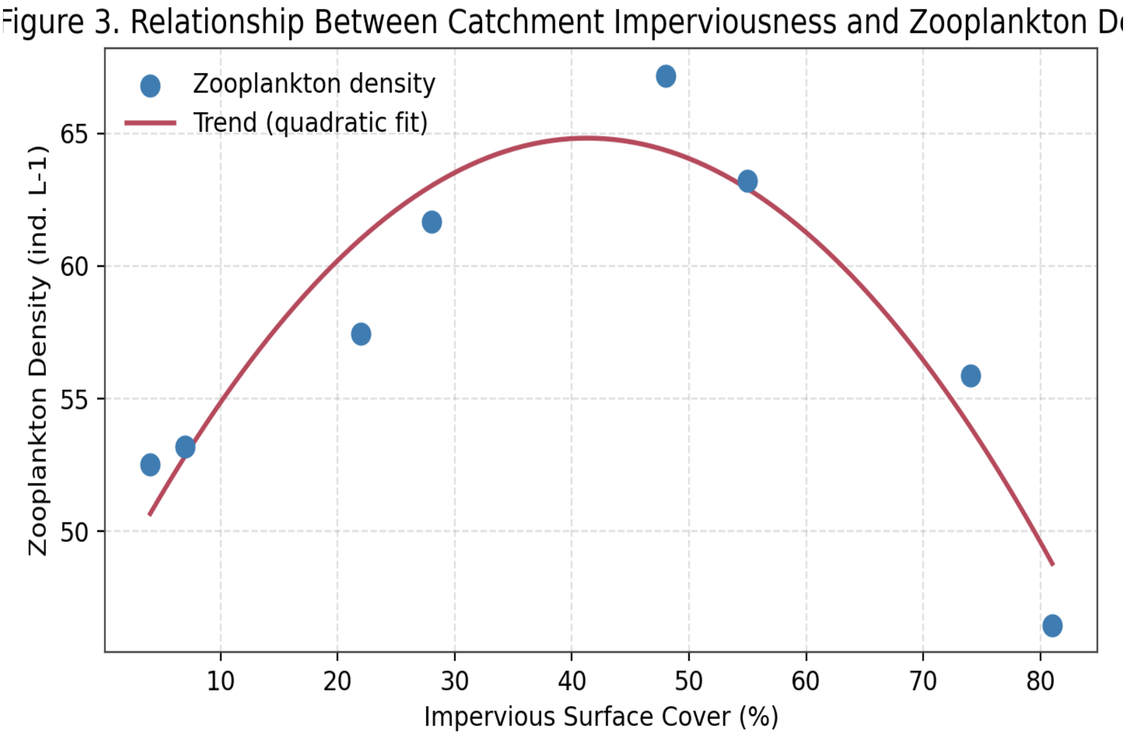

Figure 3. Zooplankton density shows a unimodal (subsidy-stress) relationship with catchment impervious surface cover, increasing at intermediate urbanization and declining at the highest levels of imperviousness.

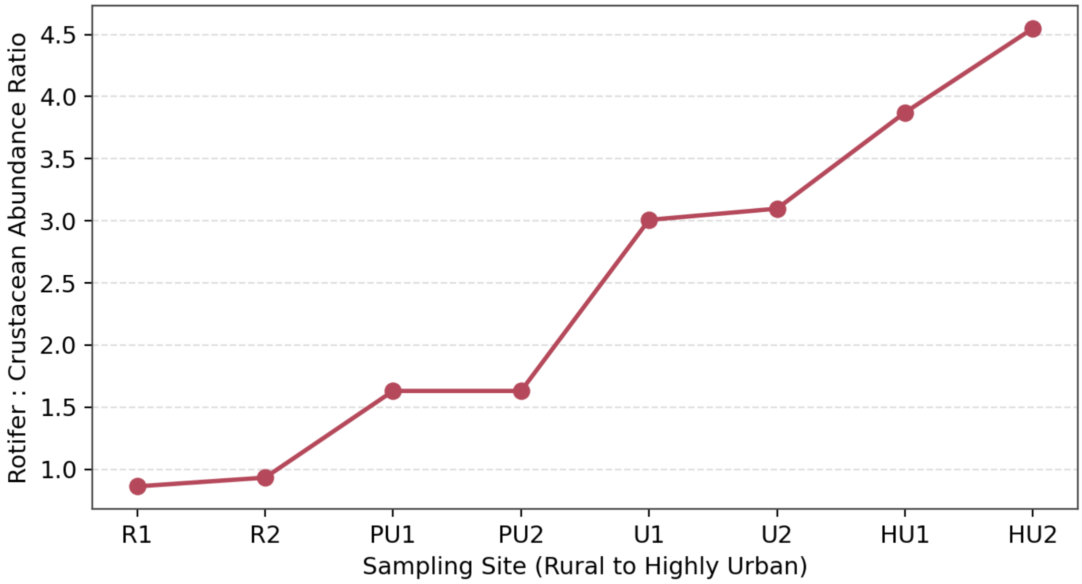

Figure 4. Progressive increase in the rotifer-to-crustacean abundance ratio with increasing catchment imperviousness.

3.4 Relationships Between Urbanization and Zooplankton Metrics

Correlation analysis confirmed strong, statistically significant relationships between catchment imperviousness and zooplankton diversity metrics (Table 3). Impervious surface cover was strongly negatively correlated with both Shannon diversity ($r = -0.94$, $p < 0.001$) and taxa richness ($r = -0.97$, $p < 0.001$), and strongly positively correlated with the rotifer-to-crustacean ratio ($r = 0.96$, $p < 0.001$). In contrast, the linear correlation between imperviousness and zooplankton density was weak and non-significant ($r = 0.12$, $p = 0.78$), consistent with the unimodal, subsidy-stress relationship visible in Figure 3, whereby a second-order polynomial fit captured the initial increase and subsequent decline in density far better than a linear model. Total phosphorus and chlorophyll-a were, as expected, very strongly positively correlated ($r = 0.98$, $p < 0.001$), confirming that the urbanization gradient investigated was accompanied by a coherent gradient of nutrient enrichment.

Table 3. Pearson correlation coefficients between catchment imperviousness, water-quality variables, and zooplankton community metrics.

Variable Pair	Pearson r	p-value	Interpretation
Impervious surface vs. Shannon H'	-0.94	< 0.001	Strong negative correlation
Impervious surface vs. Taxa richness	-0.97	< 0.001	Strong negative correlation
Impervious surface vs. Rotifer:Crustacean ratio	0.96	< 0.001	Strong positive correlation
Total phosphorus vs. Chlorophyll-a	0.98	< 0.001	Strong positive correlation
Chlorophyll-a vs. Zooplankton density	0.71	0.048	Moderate positive correlation
Impervious surface vs. Zooplankton density	0.12	0.78	No significant relationship (unimodal pattern)

4. Discussion

4.1 Diversity Loss Along the Urbanization Gradient

The steep decline in zooplankton taxa richness and Shannon diversity observed along the urbanization gradient is consistent with the broader literature on the urban stream syndrome and its lentic analogues, in which increased impervious surface cover drives more variable hydrology, higher nutrient and contaminant loading, and simplified habitat structure. These pressures act cumulatively to filter out taxa with narrow environmental tolerances, particularly larger cladocerans and calanoid copepods that are sensitive to fluctuating temperature, oxygen, and food-quality conditions. The parallel decline in Pielou's evenness suggests that urban assemblages were increasingly dominated by a small number of highly tolerant taxa, a pattern characteristic of biotic homogenization under anthropogenic stress.

4.2 The Rotifer-to-Crustacean Ratio as a Sensitive Indicator

The rotifer-to-crustacean ratio showed the strongest and most consistent response of all metrics examined, increasing steadily and predictably with catchment imperviousness. This pattern likely reflects the combination of high reproductive rates, short generation times, and generally greater tolerance to fluctuating water quality exhibited by rotifers relative to most crustacean zooplankton, together with increased predation pressure on larger cladocerans in urban systems that often support higher densities of planktivorous fish. Given its strong correlation with imperviousness and its relative ease of measurement compared to full diversity indices, the rotifer-to-crustacean ratio appears to be a particularly cost-effective indicator suitable for rapid-assessment monitoring programs with limited taxonomic resolution.

4.3 Unimodal Response of Zooplankton Density

The unimodal relationship between zooplankton density and catchment imperviousness is consistent with a subsidy-stress conceptual model, in which moderate nutrient enrichment at peri-urban and urban sites initially subsidizes phytoplankton production and, in turn, zooplankton food availability, before the cumulative stresses associated with the most heavily urbanized catchments, including toxicant exposure, extreme hydrological variability, and habitat simplification, override this subsidy and suppress overall secondary production. This finding underscores an important methodological point: total density or biomass alone is an unreliable indicator of ecological condition in urban water bodies, because moderately impacted sites may exhibit density values as high as, or higher than, reference sites even as diversity and community structure deteriorate markedly. Composite indicators that integrate both structural (diversity, evenness) and compositional (rotifer:crustacean ratio) information are therefore recommended over density-based metrics alone.

4.4 Management Implications

These findings support the incorporation of zooplankton-based metrics into routine urban water-body monitoring frameworks, complementing existing physicochemical and phytoplankton-based assessments. In particular, the combination of Shannon diversity and the rotifer-to-crustacean ratio provided clear, statistically robust discrimination among rural, peri-urban, urban, and highly urban conditions, and both metrics can be derived from relatively modest sampling and identification effort. Incorporating such indicators into stormwater management and urban water-body restoration programs could help managers detect early signs of ecological degradation before more conspicuous impacts, such as fish kills or harmful algal blooms, become apparent.

4.5 Limitations and Future Research

This study examined eight sites over a single seasonal cycle, and inter-annual variability in zooplankton community structure was not assessed. Future research should extend sampling across multiple years and seasons, incorporate functional trait-based indices (for example, body size distributions and feeding-mode composition) in addition to taxonomic indices, and evaluate the responses of zooplankton indicators to specific management interventions such as riparian buffer restoration or stormwater treatment wetlands, in order to establish reference conditions and recovery trajectories more precisely.

5. Conclusion

This study demonstrates that zooplankton community metrics respond strongly and predictably to catchment urbanization in lentic freshwater systems. Taxa richness and Shannon diversity declined steeply, and the rotifer-to-crustacean ratio increased more than five-fold, along a gradient from rural to highly urbanized catchments, while zooplankton density exhibited a unimodal subsidy-stress response that would have been overlooked by density-based assessment alone. These results confirm the value of zooplankton, and particularly compositional indices such as the rotifer-to-crustacean ratio, as sensitive, ecologically meaningful, and cost-effective indicators of ecological functioning for the assessment and management of urban and urbanizing freshwater ecosystems.

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