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RESEARCH ARTICLE

Field assessment of biologically inspired shoreline armouring methods on freshwater fish communities

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ABSTRACT

Shoreline alteration from human development and armouring is a major driver of biodiversity loss in freshwater ecosystems. While biologically inspired shoreline armouring has been explored in marine systems, its application in freshwater remains limited. This study advances freshwater research by moving from lab-based choice experiments to field trials, allowing fish to interact freely with textured panels under natural conditions. We compared fish community assemblages across 4 shoreline treatments: natural, textured panel, flat panel, and altered shorelines. Fish abundance, species richness, and diversity indices were assessed using snorkelling surveys over a single summer season. Species-specific patterns emerged. Bluegill and pumpkinseed were most abundant across all treatments, whereas textured panels supported higher abundances of largemouth and smallmouth bass, particularly young-of-the-year individuals. Age-class composition and proximity distributions differed significantly among treatments for several species, indicating treatment-specific habitat use rather than changes in overall diversity. These findings suggest shoreline modification influences fish community composition and spatial use more strongly than overall abundance or richness, especially within largely natural landscapes. Despite their limited size and short deployment, textured panels may provide functional habitat for select species, highlighting the importance of species-specific responses in evaluating eco-engineered shoreline designs.

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fish habitat; freshwater biodiversity; shoreline erosion; shoreline hardening

Introduction

Freshwater ecosystems are among the most threatened ecosystems globally (Albert et al. 2021). Reductions in biodiversity within freshwater environments surpass those observed in even the most severely impacted terrestrial ecosystems (Dudgeon et al. 2006, Reid et al. 2019). These dynamic and interconnected habitats play a vital role in maintaining biodiversity, delivering ecosystem services and supporting human livelihoods (Boulton et al. 2016, Lynch et al. 2023). However, constructed habitat alterations are causing widespread species decreases, adding to the freshwater biodiversity crisis (Tickner et al. 2020). Shoreline alterations modify nearshore habitat structures and affect ecological processes (Strayer and Findlay 2010). When natural shorelines are replaced with hardened structures like bulkheads, retaining walls, and other erosion control measures, habitat complexity is decreased, resulting in changes in species composition and decreased diversity of fish and invertebrates (Gittman et al. 2016, Wensink and Tiegs 2016). Importantly, these changes may not affect all species equally; generalist and habitat-specialist fishes can differ markedly in their responses to altered shoreline structure. For example, in the Salish Sea, armoured shorelines were associated with reductions in forage fish spawning habitat, whereas more mobile or generalist species were less affected (Dethier et al. 2016). Similarly, in freshwater systems, littoral species that rely on structurally complex nearshore habitats, such as centrarchids, have been shown to decline along hardened shorelines, whereas tolerant or habitat-generalist species may persist (Wensink and Tiegs 2016, Chhor et al. 2020). These species-specific and structural responses are central to understanding biodiversity outcomes, as shoreline modifications may alter not only total abundance, but also community composition, demographic structure, and the relative abundance of taxa within freshwater systems.

In addition to causing local habitat degradation, shoreline armouring can alter the connectivity of habitats between nearshore and offshore zones, which is crucial for the migration, feeding, and life-history processes of mobile fish species. To facilitate energy flow and resource coupling throughout lake ecosystems,

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nearshore habitats often serve as crucial transition zones, connecting littoral, pelagic, and benthic environments (Schindler and Scheuerell 2002, Vander Zanden and Vadeboncoeur 2002). Fish can migrate between habitats and integrate resources across zones thanks to hydrologic connections between coastal wetlands and nearshore areas, which sustain trophic dynamics and food web structure (Sierszen et al. 2019). By limiting access to spawning grounds, shelter, or foraging habitats, the structural simplicity of shorelines may break these connections, impacting wider ecosystem processes even when the impacts seem isolated. Such disruptions may influence not only overall fish abundance, but also which species are able to persist or flourish within modified nearshore habitats.

Given the vital significance that rivers, lakes, and canals play as habitats for a wide variety of aquatic species, it is important to identify how shoreline modifications impact freshwater biodiversity (Naiman et al. 2010). The intricate relationships that these ecosystems foster between organisms and their environments may be hindered by hardened shorelines (Schindler and Scheuerell 2002, Wensink and Tiegs 2016). In urban rivers, where concrete retaining walls are common, the effects of shoreline constructions are particularly noticeable (Gittman et al. 2016). These changes are not specific to any one area because many nations struggle to balance the preservation of habitat and effective erosion control measures (Ostendorp et al. 2020). While concrete retaining walls excel in their primary role of erosion control, their ecological consequences have raised concerns. The transition from natural habitats to concrete structures reduces habitat complexity, potentially leading to negative consequences for aquatic ecosystems (Storesund et al. 2008, Cooke et al. 2020). Such reductions in complexity may favor more tolerant or opportunistic species while disadvantaging species with specific habitat requirements. Despite ecological consequences, waterfront property owners continue to use hardened structures to prevent erosion and preserve the integrity of their properties (Scyphers et al. 2019).

Assessing shoreline armoring methods that lessen habitat degradation and biodiversity loss is becoming increasingly crucial (Gittman et al. 2016). Concrete, valued for its durability and versatility, has come to the forefront of this discussion (Makul 2020). Although concrete is still an essential part of contemporary infrastructure such as highways, buildings, and dams, its ecological impacts in aquatic environments require more investigation (Cooke et al. 2020). Understanding the interactions between human construction and ecosystems is essential to exploring how structures can be adapted to better support aquatic biodiversity (Johnson et al. 2017). Retaining walls used for coastal defense against erosion and flooding may unintentionally alter littoral environments and reduce nearshore biodiversity (Chhor et al. 2020). While preserving natural shorelines is the ecologically ideal approach, it is not always feasible, and some shorelines must be armored to protect human interests. As a result, interest is growing for modifying concrete designs that support both structural development and biodiversity conservation in freshwater systems. Previous research has shown that engineered structures can effectively replicate the multifaceted conditions of natural habitats to support a rich diversity of species (Bishop et al. 2022). With living shorelines as the only substitute for hardened waterfronts, conservation advantages were typically achieved through an "all or nothing" strategy prior to this new trend in marine-friendly bulkhead construction. Alternative methods incorporating naturally inspired erosion control systems alongside constructed shorelines are showing promising results in marine settings but have yet to be explored within freshwater ecosystems. However, whether such engineered habitats support a broad diversity of species or primarily benefit a subset of the fish community remains unclear.

To this end, we investigated the performance of 4 different shoreline types: natural, textured panel, flat panel, and altered shorelines, to see how engineered concrete shoreline erosion control innovations can sustain a variety of freshwater biodiversity. Natural shorelines served as the baseline of unmodified conditions while engineered treatments (textured panel, flat panel, and altered shorelines) offered differing degrees of structural change. These shoreline treatments were chosen to reflect a gradient of habitat complexity typically seen in freshwater habitats. We specifically looked at the effects of these shoreline types on important biodiversity measures such as species richness, diversity, and abundance. Building on earlier laboratory research (Frempong-Manso et al. 2024, 2025), this study shifts to a field-based approach to evaluate how wild, free-swimming freshwater fishes interact with textured panels under natural conditions, where they have full autonomy to choose among available habitats. In this context, engagement is defined as patterns of habitat association, quantified through fish abundance, species composition, and spatial proximity to shoreline treatments rather than direct behavioural interactions. Rather than testing whether artificial structures can immediately match the biodiversity of natural habitats, our main objective was to assess how fish associate with textured structures relative to other shoreline types and whether these initial patterns of habitat use indicate potential for supporting freshwater biodiversity. This study will contribute to future research that looks at the long-term ecological effects of shoreline armouring designs for erosion control and to a growing

body of research on the importance of how design elements influence habitat uses.

Materials and methods

Study site

This research project was carried out at Queen's University Biological Station (QUBS) on Opinicon Lake, an 889.9 ha lake in eastern Ontario (average depth 2.5 m and maximum depth 11 m) that supports a variety of aquatic species (Keast and Harker 1977). The abundance of fish species, including populations of predators and prey, makes the area perfect for researching the potential effects of enhanced shoreline designs on fish habitat and biodiversity. During this experiment we saw the following species: bluegill (*Lepomis macrochirus*), pumpkinseed (*L. gibbosus*), rock bass (*Ambloplites rupestris*), yellow perch (*Perca flavescens*), smallmouth bass (*Micropterus dolomieu*), largemouth bass (*M. salmoides*), minnow species (Family *Cyprinidae*), northern pike (*Esox lucius*), log perch (*Percina caprodes*), and banded killifish (*Fundulus diaphanus*).

Site selection

Fieldwork began on 2 July 2024 and continued until 26 August 2024, consisting of 9 weekly snorkeling surveys at 5 sites. Each site included all 4 shoreline treatment types. To reflect the wide variety of shoreline types available in the lake's ecosystem, including differences in natural flora, substrate composition, and level of human impact, sites were selected (Fig. 1) based on similarity of flora, substrate characteristics, and levels of human disturbance (such as boating or fishing) to minimize underlying habitat variability and focus on potential interactions between various erosion control designs and shoreline circumstances. To minimize any potential impact on fish distribution, introduced structures were placed a few meters apart from both natural and altered shoreline areas. The 4 types of panels (treatments) were installed at each location to evaluate their effects on biodiversity and fish habitat. (1) Natural (Fig. 2a) consisted of unaltered shoreline condition to represent a fully natural environment. Natural shorelines at the study sites were primarily rocky, except for 1 sandy site. All natural shorelines were relatively shallow and not steep and vegetation density was low. (2) Altered shorelines (Fig. 2b) included any preexisting physical modifications such as docks, boat slips, and other constructed alterations. (3) Flat panel (Fig. 2c) consisted of a traditional shoreline hardening method, specifically a flat retaining wall. (4) Textured panel (Fig. 2d) incorporated natural forms in the panel design. Water depth within the monitored distance from the shore to the sites ranged from 0.914 to 1.219 m. Textured and flat panels were positioned ~5 m from the shoreline, and all treatments were positioned ~10 m apart from each other. The textured panels were constructed using the same method as Frempong-Manso et al. (2025). Panels were deployed ~5 m from the shoreline because availability of fully armored shoreline at the study sites was limited. To evaluate initial habitat utilization while reducing variability in adjacent habitat, we mainly observed interactions at the front-facing side of the panels. Monitoring began 2 weeks after installation for the textured and flat panels to allow initial settlement and to minimize disturbance effects. Although not always possible, we attempted to distribute the treatment panels at equal distances from each other among the 5 sites. The study was conducted in clear weather between 0900 and 1600 h, excluding crepuscular intervals when changes in the fish communities could be anticipated.

Sampling metrics

To reduce the possibility that equipment could affect fish behaviour, a single snorkeler used a standard kit (black mask, black snorkel, black fins, and black wetsuit) to survey every treatment type. Surveys followed the Salmonid Field Protocols Handbook (O'Neal 2007). With the swimmer swimming steadily 1.27 m out from the treatment and gazing slightly toward the treatment, the field of sight was restricted to the space between the swimmer and the shore (O'Neal 2007). To determine how each shoreline type affected fish communities, we collected data on fish abundance, species richness, age, and fish proximity at each site. To avoid double counting, fish were tallied and identified when they passed (O'Neal 2007). Every observation was made with a pencil on a PVC diving slate while submerged. Fish were identified to the best of ability of the surveyor; in the event the fish could not be identified, details of the fish's appearance was noted on the dive slate, and fish guides were consulted to make the identification. Fish were categorized into 3 age groups: juvenile, adult, and young-of-the-year by combining visual evaluations of morphological traits with estimates of body size. The smallest individuals were designated young-of-the-year, usually born in the same year as the data collection, and had immature but fast-growing characteristics. Adults were recognized as completely mature fish based on body size, fin development, and general morphology, whereas juveniles were characterized by intermediate body size and developing traits suggestive of sub-adulthood. To determine

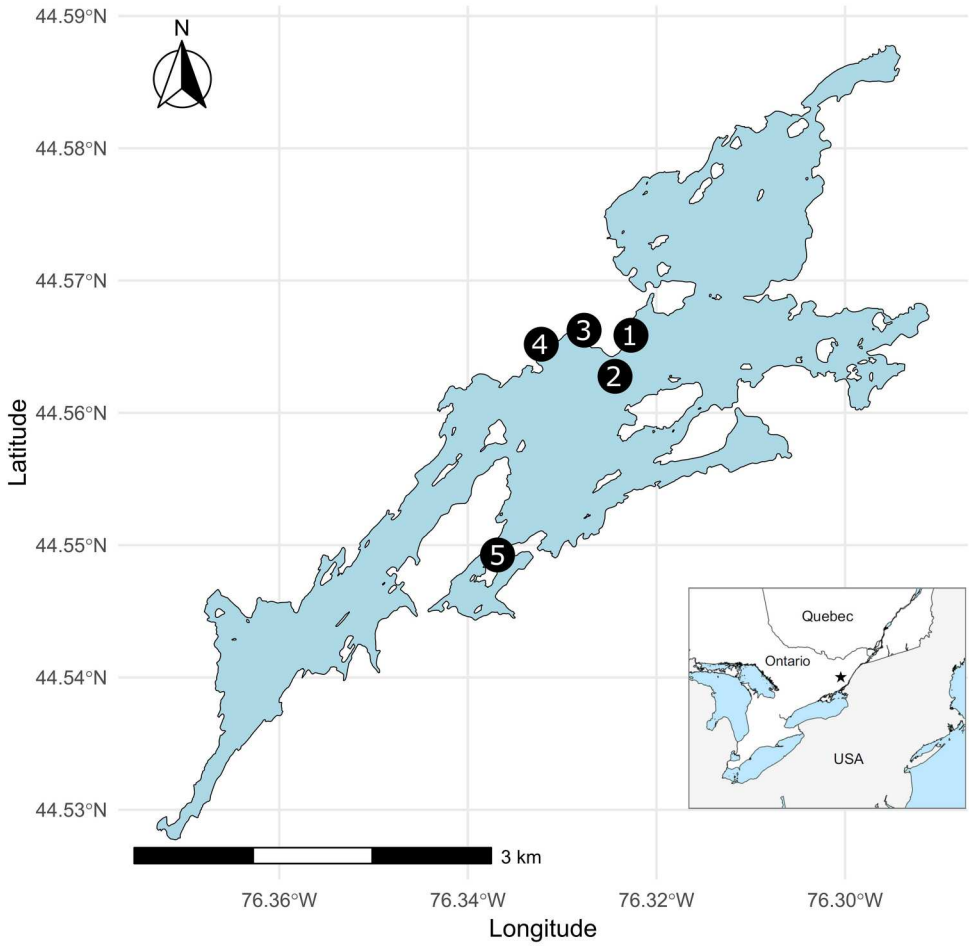

Figure 1. Study sites around Opinicon Lake, Ontario, where shoreline treatments were installed and fish surveys were conducted. The sites were selected to represent a range of shoreline conditions and human modifications.

spatial preferences in relation to shoreline treatments, fish proximity to treatment types was divided into 3 different proximity ranges: near (0–0.254 m), intermediate (0.2794–0.762 m), and far (>0.787 m). Markers were placed on the substrate at these distances to ensure the snorkeler could consistently identify and record fish within each proximity category. By examining fish diversity and abundance at different distances from each treatment type, these categories offered valuable information about habitat usage patterns and possible avoidance or attraction behaviours in response to both natural and artificial shoreline features (Fig. 3). Weekly monitoring recorded short-term ecological responses to the shoreline treatments.

Data analysis

R 4.4.1 was used to conduct statistical analyses (R Core Team 2024) with the *dplyr* (Wickham et al. 2023), *tidyr* (Wickham et al. 2024), *broom.mixed* (Bolker et al. 2024), and *janitor* (Firke et al. 2025) packages for data cleaning and formatting. Data were initially screened for inconsistencies and missing values; entries with incomplete key fields were then excluded from the analysis. Rare species (≤5 total observations across all sites) were removed, and numeric columns were standardized using a *z*-score transformation. Several statistical analyses were conducted to examine how treatment type affected species diversity, species richness, total abundance, and species-specific age and proximity distributions.

The effects of treatment type and species identity on species abundance were examined using a linear mixed-effects model (LMM) using the *lme4* (Bates et al. 2015), *lmerTest* (Kuznetsova et al. 2017), and *emmeans* (Lenth 2024) packages with site as a random effect to account for spatial heterogeneity. This approach was selected because it appropriately handles data structured by sites and allows for partitioning of both fixed effects (treatment type, species) and random variation due to site, which is important for ecological datasets exhibiting spatial dependence. Species-specific abundances were modeled with treatment type and species as fixed

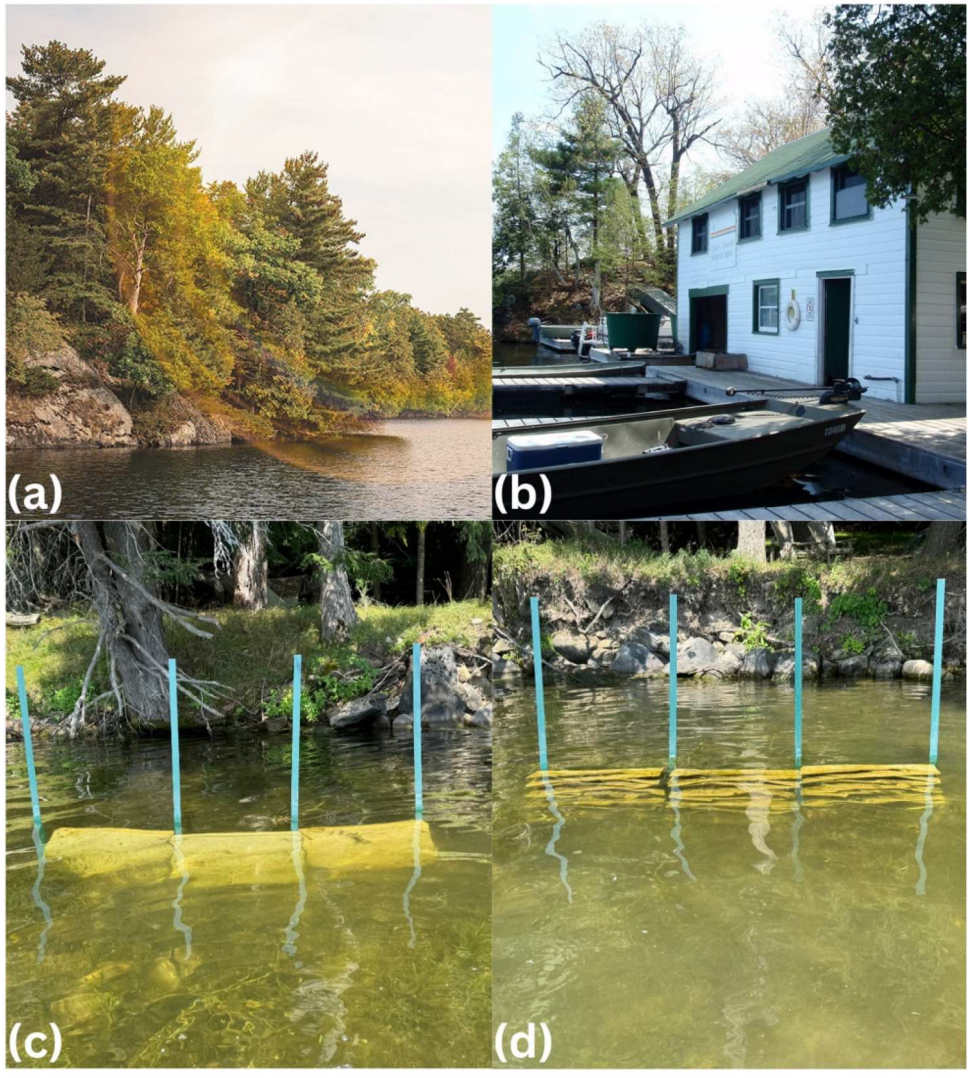

Figure 2. Examples of the 4 shoreline treatment types used in the Opinicon Lake, Ontario, study: (a) natural shoreline, representing unaltered conditions with native vegetation and substrate; (b) altered shoreline, including constructed modifications such as docks and boat slips that impact habitat structure; (c) flat panel, a traditional smooth concrete panel to represent standard shoreline armouring; and (d) textured panel.

effects, and overall abundance was calculated as the total number of individuals per species across all sites.

To evaluate whether age-class distributions differed among shoreline treatments for each species, we constructed species-specific contingency tables of age class (young of the year, juvenile, adult) by treatment type. Fisher's exact tests (with 10 000 simulated replicates) were used to test for independence between age class and treatment, an appropriate approach for categorical count data selected because several species had small cell counts that could violate assumptions of basic chi-squared contingency tests. The same procedure was applied to examine the proximity categories near, intermediate, and far by treatment type for each species.

Community-level diversity metrics were calculated from species abundances, including species richness, Shannon diversity, evenness, and total abundance per site using the *vegan* package (Oksanen et al. 2024). The effects of treatment type on these diversity metrics and total abundance were evaluated using LMMs for species richness, Shannon diversity, and total abundance, and a linear model for evenness, with site included as a random effect for the mixed models. Summary statistics (mean [standard error]) were calculated for visualization. All figures were created using *ggplot2* (Wickham 2016), and all statistical tests were conducted with a significance level of $\alpha = 0.05$.

Results

Fish abundance varied among species and treatments, although total abundance did not differ significantly

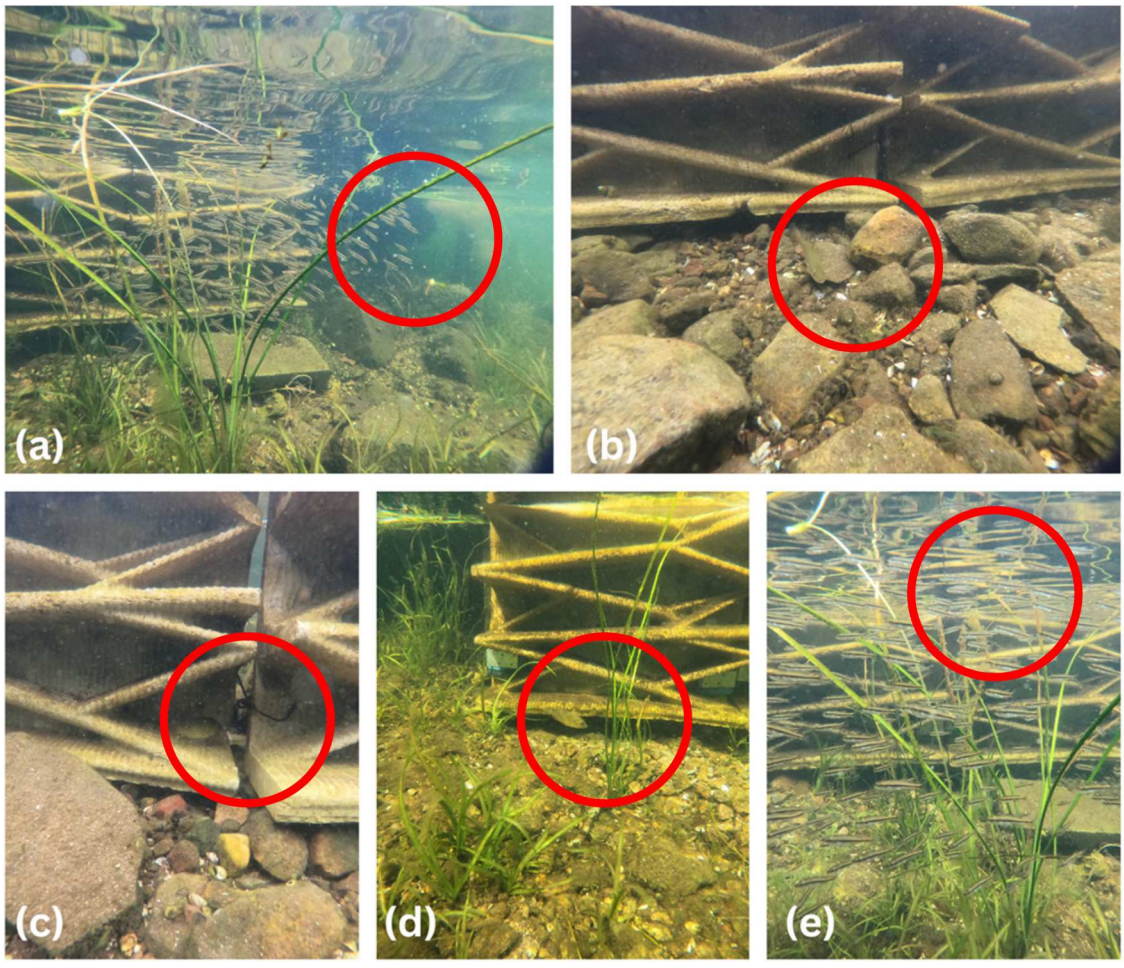

Figure 3. Juvenile fish species observed interacting with the textured panel treatment. (a) smallmouth bass, (b) largemouth bass, (c) rock bass, (d) bluegill, (e) smallmouth bass. These images demonstrate fish presence and potential habitat use of the textured shoreline modification.

across treatments. Linear mixed models showed no significant effect of treatment type on total abundance (LMM, $F_{3,15} = 0.444$, $p = 0.726$; Table 1). Similarly, diversity metrics, including species richness ($F_{3,10.8} = 0.735$, $p = 0.546$; Fig. 4), Shannon diversity ($F_{3,10.8} = 0.574$, $p = 0.644$; Fig. 5), and species evenness ($F_{3,16} = 0.505$, $p = 0.685$; Fig. 6) did not differ significantly among treatments. Random effects analyses revealed that site-level variation had a significant influence on species richness using the likelihood ratio test (LRT = 4.05,

Table 1. Linear mixed model results for diversity metrics and total abundance across shoreline treatments in Opinicon Lake, Ontario. LRT is the likelihood ratio test.

Metric	Fixed effect	*F*	df	*P*	Random effect site LRT (*p*)
Species richness	Treatment type	0.735	3,16	0.546	4.05 (0.044)
Shannon diversity	Treatment type	0.574	3,16	0.644	2.08 (0.149)
Species evenness	Treatment type	0.505	3,15	0.685	—
Total abundance	Treatment type	0.444	3,10.8	0.726	0.739 (0.390)

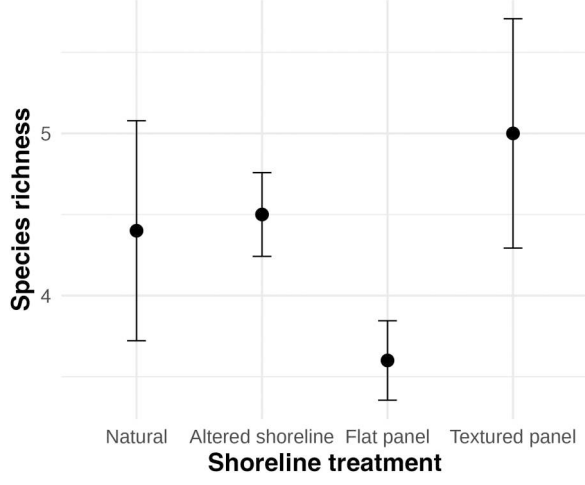

Figure 4. Mean species richness (standard error bars) across 4 shoreline treatments ($n = 5$ sites per treatment): natural shoreline, altered shoreline, flat panel, and textured panel. Each point represents the mean number of unique fish species observed per site within each treatment type.

$p = 0.044$), but not on Shannon diversity or total abundance (Table 1; Fig. 7).

Across all shoreline treatments, 2033 individual fish were observed. Bluegill and pumpkinseed were the most abundant species in all treatments. A total of 518 individuals were found on altered shorelines, with bluegill (325) and pumpkinseed (149) being the most common species. Minnows (16), yellow perch (10), rock bass (6), banded killifish (4), largemouth bass (4), smallmouth bass (3), and pike (1; Table 2) were found in smaller numbers. Flat panels supported the highest total abundance (548 individuals), with bluegill (336) and pumpkinseed (181) again most abundant, followed by minnows (17), yellow perch (7), rock bass (1), largemouth bass (3), and smallmouth bass (3). Natural shorelines had 512 individuals, led by bluegill (328) and pumpkinseed (140), with minor contributions from smallmouth bass (8), yellow perch (9), minnows (23), and low counts of largemouth bass (3) and log perch (1, exclusive to this treatment). Textured panels had the lowest total abundance (455 individuals) but supported the highest counts of largemouth (43) and smallmouth bass (14), alongside bluegill (274), pumpkinseed (78), minnows (26), rock bass (12), and yellow perch (8).

Age-class distribution patterns differed by treatment and species (Tables 3 and 4). Bluegill and pumpkinseed populations were dominated by juveniles and adults across all treatments (Table 4), whereas bass species, especially largemouth bass, were mostly young-of-the-year on flat and textured panels. Fisher's exact tests for age × treatment showed that bluegill, pumpkinseed, largemouth bass, minnow, and rock bass had significantly different age structures (Table 3), whereas smallmouth bass and yellow perch did not. For instance, the bluegill age structure was relatively evenly split between juveniles and adults across treatments, despite statistically significant differences among treatments (Tables 3 and 4). By contrast, almost all largemouth bass observed on textured panels were young-of-the-year (97.6%: 42 of 43 individuals; Table 4).

Similarly, proximity distributions differed among species and treatments (Tables 5 and 6). While bass

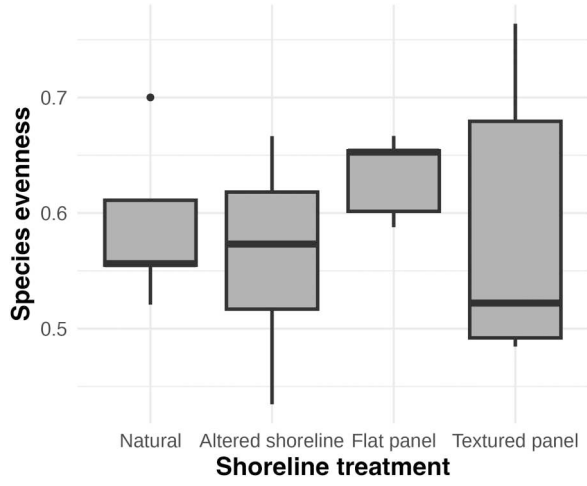

Figure 6. Species evenness across 4 shoreline treatments in Opinicon Lake, Ontario ($n = 5$ sites per treatment). Boxplots show the median (central line), interquartile range (box), and whiskers extending to the most extreme values within 1.5 times the interquartile range. Evenness indicates how evenly individuals are distributed among species within each site.

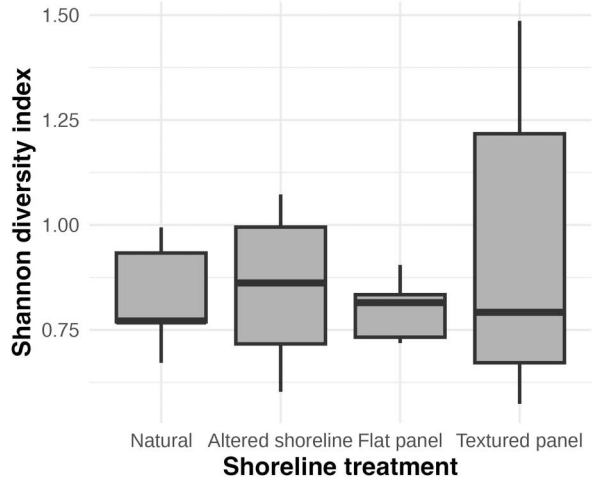

Figure 5. Shannon diversity index values across 4 shoreline treatments in Opinicon Lake, Ontario ($n = 5$ sites per treatment). Boxplots display the median (central line), interquartile range (box), and whiskers extending to the most extreme values within 1.5 times the interquartile range. Shannon diversity reflects both species richness and evenness within each site.

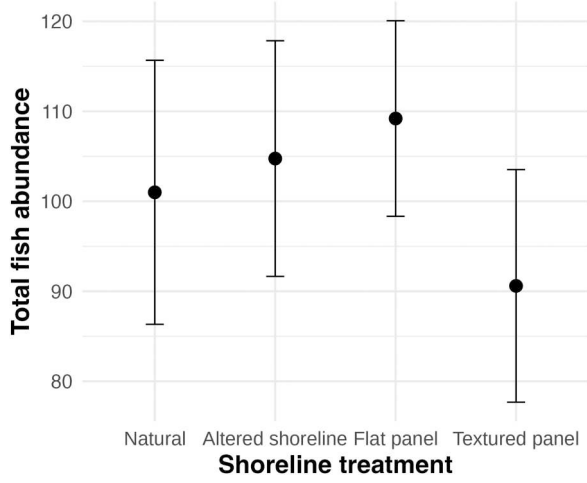

Figure 7. Mean total fish abundance (standard error bars) across 4 shoreline treatments in Opinicon Lake, Ontario ($n = 5$ sites per treatment). Each point represents the mean total number of individual fish observed per site within each treatment type.

Table 2. Total fish counts per species across shoreline treatments in Opinicon Lake, Ontario.

Species	Natural	Altered shoreline	Flat panel	Textured panel
Bluegill	328	325	336	274
Pumpkinseed	140	149	181	78
Minnow	23	16	17	26
Yellow perch	9	10	7	8
Rock bass	0	6	1	12
Largemouth bass	3	4	3	43
Smallmouth bass	8	3	3	14
Banded killifish	0	4	0	0
Pike	0	1	0	0
Log perch	1	0	0	0
Total	512	518	548	455

Table 3. Fisher's exact test (simulated) results for age–class distributions by species across treatments.

Species	*P*
Bluegill	0.0001
Largemouth bass	0.0001
Minnow	0.0039
Pumpkinseed	0.0001
Rock bass	0.0404
Smallmouth bass	0.178
Yellow perch	0.174

species were frequently located closer to panels, bluegill and pumpkinseed were observed at all proximity intervals, with most individuals occurring at far (>0.787 m) and intermediate (0.2794–0.762 m) distances (Table 6). For bluegill, largemouth bass, rock bass, and smallmouth bass, Fisher's exact tests for proximity × treatment showed significant differences (Table 5), whereas minnow, pumpkinseed, and yellow perch did not. For instance, rock bass were predominantly observed near textured panels (83.3%; Table 6) while smallmouth bass

Table 5. Fisher exact test (simulated) results for proximity distributions by species.

Species	*P*
Bluegill	0.0001
Largemouth bass	0.0256
Minnow	0.0875
Pumpkinseed	0.139
Rock bass	0.0286
Smallmouth bass	0.0442
Yellow perch	0.184

were more evenly distributed between near and intermediate distances on textured panels (Table 6). By contrast, nearly all largemouth bass associated with textured panels were observed at far distances (95.2%; Table 6).

Overall, treatment type had a substantial impact on species-specific age-class composition and proximity distributions, even when total abundance and species richness did not differ significantly among shoreline treatments. Textured panels were more frequently associated with bass species, particularly young-of-the-year largemouth and smallmouth bass, whereas bluegill and pumpkinseed remained consistently abundant across treatments (Tables 4 and 6). These findings suggest that shoreline modification influences community composition and spatial distribution rather than overall abundance. Panel performance also varied among sites, highlighting the importance of local environmental conditions surrounding each installation.

Discussion

Shoreline modifications, especially hardened structures, are often employed to reduce erosion but can

Table 4. Age-class frequencies by species and treatment type.

		Treatment Type			
Species	Age Class	Natural	Altered shoreline	Flat panel	Textured panel
Bluegill	Young-of-the-year	0.6%	3.5%	3.6%	2.2%
	Juvenile	55.5%	51.6%	64.0%	40.0%
	Adult	43.9%	45.0%	32.4%	57.8%
Largemouth bass	Young-of-the-year	0.0%	0.0%	100.0%	97.6%
	Juvenile	100.0%	33.3%	0.0%	2.4%
	Adult	0.0%	66.7%	0.0%	0.0%
Minnow	Young-of-the-year	0.0%	0.0%	29.4%	3.8%
	Juvenile	9.1%	0.0%	17.6%	7.7%
	Adult	90.9%	100.0%	52.9%	88.5%
Pumpkinseed	Young-of-the-year	3.7%	14.5%	2.2%	0.0%
	Juvenile	43.4%	33.3%	43.8%	21.8%
	Adult	52.9%	52.2%	53.9%	78.2%
Rock bass	Young-of-the-year	–	25.0%	–	0.0%
	Juvenile	–	75.0%	–	33.3%
	Adult	–	0.0%	–	66.7%
Smallmouth bass	Young-of-the-year	100.0%	100.0%	0.0%	60.0%
	Juvenile	0.0%	0.0%	66.7%	40.0%
	Adult	0.0%	0.0%	33.3%	0.0%
Yellow perch	Young-of-the-year	0.0%	0.0%	0.0%	0.0%
	Juvenile	55.6%	30.0%	85.7%	50.0%
	Adult	44.4%	70.0%	14.3%	50.0%

Table 6. Proximity frequencies by species and treatment type.

		Treatment Type			
Species	Proximity	Natural	Altered shoreline	Flat panel	Textured panel
Bluegill	Near	10.5%	17.5%	17.2%	17.5%
	Intermediate	24.0%	32.0%	25.4%	40.0%
	Far	65.5%	50.5%	57.4%	42.5%
Largemouth bass	Near	0.0%	0.0%	50.0%	2.4%
	Intermediate	100.0%	0.0%	0.0%	2.4%
	Far	0.0%	100.0%	50.0%	95.2%
Minnow	Near	22.7%	0.0%	5.9%	12.5%
	Intermediate	40.9%	56.3%	82.4%	62.5%
	Far	36.4%	43.8%	11.8%	25.0%
Pumpkinseed	Near	9.7%	12.1%	6.7%	5.1%
	Intermediate	26.1%	33.6%	28.3%	39.7%
	Far	64.2%	54.3%	65.0%	55.1%
Rock bass	Near	–	25.0%	–	83.3%
	Intermediate	–	0.0%	–	8.3%
	Far	–	75.0%	–	8.3%
Smallmouth bass	Near	25.0%	0.0%	0.0%	42.9%
	Intermediate	50.0%	0.0%	0.0%	42.9%
	Far	25.0%	100.0%	100.0%	14.3%
Yellow perch	Near	0.0%	10.0%	0.0%	14.3%
	Intermediate	11.1%	20.0%	42.9%	57.1%
	Far	88.9%	70.0%	57.1%	28.6%

*Proximity categories were defined as follows: near (0–0.254 m), intermediate (0.2794–0.762 m), and far (>0.787 m).

themselves alter the complexity of habitats, potentially influencing species diversity directly. To better evaluate the ecological effects of shoreline treatments, a comprehensive understanding of their impact on freshwater fish communities is needed. Our study examined how fish abundance, diversity, and community composition responded to 4 shoreline treatment types: natural shorelines, textured panels, flat panels, and altered shorelines.

Contrary to our initial expectations, overall fish abundance and diversity metrics did not differ significantly among shoreline treatments. Fish abundances were numerically highest on flat panels and lowest on textured panels, with natural and altered shorelines intermediate, although these differences were not statistically significant. This finding suggests that, at the scope of our investigation, treatment type had no effect on broad diversity metrics or overall fish abundance when placed in relatively small sample sizes in mostly natural surroundings. In some cases, flat panels supported greater fish abundance than natural shorelines. This conclusion is surprising, but natural shorelines can have complex habitat elements like dense vegetation and coarse woody debris, which may allow fish to retreat or remain hidden during snorkel surveys. Therefore, rather than reflecting actual variations in overall fish population, apparent changes in observed abundance may also reflect variations in detectability and habitat effects. These results suggest that, at the scale of our study, treatment type did not significantly affect overall fish abundance or broad diversity measures, and that, under certain circumstances, simplified artificial structures may still offer features that are appealing or functionally suitable for specific species.

Textured panels did not support as high a species diversity as flat panels or natural shorelines even though they were designed with the intention to increase habitat complexity, but this does not imply that textured panels were ecologically ineffective. Understanding that the textured panels were set up along mostly long-standing natural shorelines, were relatively small (1.5 m length), and were recently deployed in a natural setting is crucial. The degree or scale of added complexity provided by the textured panels may not yet have been sufficient to alter whole-community diversity patterns (Morris et al. 2019). Therefore, rather than long-term habitat uses or equilibrium community responses, observed patterns might represent early-stage interactions with novel structures. Additionally, fish might not have been forced to use the panels solely because they were positioned among otherwise excellent habitat. To completely reflect how fish integrate textured habitats into their home ranges, longer deployment times and greater spatial extents could be needed, as well as consideration to the immediate and larger connectivity to natural habitats.

Species-specific responses showed substantial ecological patterns, even though overall abundance and diversity indicators were not significantly impacted by treatment type. Because of their versatility and generalist habitat utilization, bluegill and pumpkinseed were consistently prominent in all shoreline modifications. By contrast, despite the reduced total abundance seen in this treatment, largemouth and smallmouth bass were most significantly connected with textured panels, implying that rather than generally improving fish abundance, textured panels might disproportionately

benefit some taxa. This conclusion was further reinforced by age–class distributions. Young-of-the-year individuals were most common among bass species, especially on textured panels, whereas bluegill and pumpkinseed populations were dominated by juveniles and adults in all treatments. These patterns imply that textured panels might offer habitat traits particularly beneficial for specific species' early life stages, including shelter from predators or appropriate microhabitats for foraging. These results suggest that shoreline treatments may influence community structure through demographic effects rather than changes in overall abundance because early life-stage survival can have a significant impact on population dynamics.

Similarly, proximity analyses revealed that fish spatial distributions relative to shoreline treatments differed among species. Bass species tended to occur closer to panels, whereas bluegill and pumpkinseed were distributed across a wider range of distances, with most individuals observed at intermediate and far distances. Although proximity did not significantly explain variation in total abundance or richness, these results suggest that fish responded more strongly to the presence and type of shoreline treatment than to small-scale positioning relative to structure. We acknowledge that the limited proximity range (<1 m) constrains inference about broader spatial gradients, but small-scale spatial associations can still reflect edge use or localized structural interactions. These findings are consistent with previous work showing that fish distributions are often driven more by physical habitat features than by micro-scale spatial location alone (Jones 1984, Wellborn et al. 1996, Gauff et al. 2018).

When combined, our findings indicate that species composition, age structure, and spatial distribution changes rather than general shifts in abundance or diversity are the main ways that shoreline modifications affect fish communities when deployed in relatively small sections within existing natural settings. Factors such as habitat complexity, resource availability, and species-specific habitat needs and ecology may influence whether species seem to use a particular shoreline type more strongly than others (Calle et al. 2018). The varying structural characteristics of the different treatment types likely influenced the engagement with the habitats, especially for species that depend on cover for food or protection from predators (Schmitz 2007). These species-specific interactions highlight the importance of understanding how the habitat preferences of fish are influencing how they respond to eco-engineered habitats. For example, some species may choose to interact with a specific shoreline type because they depend on a physical element of that habitat, such as physical structures for spawning or refuge (Strayer and Findlay 2010). Other species may be selecting habitats based on the presence of appropriate microhabitats, such as cracks, shady spots, or surfaces that encourage a high number of prey (Underwood et al. 2004).

Understanding the habitat related behavioural patterns may help us better examine how species select and interact with their habitats. Species that prefer more highly structured habitats might actively look for treatments types that offer more surface complexity or improved predator protection (Downes et al. 1998), whereas species more opportunistic or labile in their habitat choices may be less reliant on certain habitat characteristics, resulting in less selectivity for different shoreline types (Schindler and Scheuerell 2002). Previous research has shown that a combination of species-specific characteristics and more general ecological interactions determine how fish communities respond to habitat changes (Scharf et al. 2006). Our findings reinforce the idea that eco-engineered shoreline treatments should be evaluated not only on total abundance metrics but also on their ability to support particular species and life stages.

Shoreline types differed not just in number of fishes present but also in local species composition. The most often seen species in all treatments were pumpkinseed and bluegill, reflecting their general adaptability tendency to use a variety of habitat types. Some species, however, displayed more specific relationships. Despite their lower total abundance, largemouth and smallmouth bass were most commonly found near textured panels, which may suggest that they favour more structurally complex habitats offering appropriate refuge from predators or ambush spots for foraging. Largemouth and smallmouth bass are important gamefish species with considerable socioeconomic value, and therefore our finding that they preferred textured panels over natural shorelines is promising for their habitat enhancement and potential conservation benefits. Each year, effort and resources are devoted to enhancing habitat for largemouth and smallmouth bass in lakes, rivers, and reservoirs throughout their natural and introduced ranges (Quinn and Paukert 2009). Textured panels may represent a promising tool within a broader habitat management framework, particularly for supporting early life stages of bass species, despite not increasing total abundance at the community level. Log perch, which are not considered gamefish, were only found along natural shorelines, indicating that the distribution of more specialized species may depend on specific ecological features specific to natural settings, including substrate heterogeneity or established

flora. These trends highlight the significance of considering the habitat requirements of individual local species when developing or altering shoreline treatments, and they suggest against depending exclusively on overall fish abundance as a measure of ecological value.

Limitations and future research directions

Several methodological limitations in our study should be acknowledged. One key limitation is sampling duration. Our study only collected data over 2 months, representing a late-summer snapshot. This short timeframe limited our ability to capture not only variation across seasons, but also temporal changes that may occur within the sampling period, such as week-to-week or day-to-day shifts in fish abundance and behaviour. In addition, sampling was conducted during daytime hours only, so diel variation in fish activity and habitat use was not captured. These temporal limitations may bias interpretations of habitat use and behaviour, particularly for species that exhibit crepuscular or nocturnal activity. This limitation also meant that we were unable to fully understand how organism settlement (e.g., periphyton) and invertebrate colonization influenced fish habitat use (i.e., we compared relatively "clean" concrete panels with long-standing altered and natural sites).

Furthermore, within our study we had site selection constraints because our study was conducted in a lake environment, which may not be fully representative of all armored shoreline areas. An additional limitation relates to the spatial configuration of the experimental panels. Although intended to function as shoreline enhancements, the textured panels were deployed as isolated structures within open habitat, making them more analogous to a small reef or shelter-like features than continuous shoreline armoring. As a result, fish responses observed in this study may reflect attraction to discrete structural refuges rather than responses to shoreline habitat.

We used snorkeling as a method to assess the fish community near the panels and other treatments, but the presence of the snorkeler may have influenced fish behaviour. Moreover, behavioural responses may have differed among species and size classes because body size and life stage can influence habitat use, risk perception, and detectability. Variability in size distributions across species may therefore introduce bias into behavioural assessments and should be considered in future study designs.

Another limitation to consider is the spatial scale of this study. The textured panels used in this study were small (1.5 m in length) and deployed in limited numbers within a highly interconnected lake ecosystem. Additionally, the relatively short length and recent deployment of the textured panels limit the ability to directly compare fish abundance and diversity with long-standing natural or altered shorelines. This design may not completely quantify habitat selection or preference across different habitat types, but it does capture short-term interactions and possible avoidance or attraction to novel structures. Despite these aforementioned limitations, this study represents the first field trial of engineered concrete panels with textured design features intended to enhance habitat complexity and provides important preliminary insights into how fish interact with newly introduced structures in freshwater systems.

Future research should focus on examining the long-term effects of textured panels on freshwater biodiversity over larger spatial scales (e.g., over tens of meters of shoreline emulating what would typically happen when erosion controls are installed). Incorporating continuous shoreline deployments, diel sampling, and size-structured behavioural observations would help resolve limitations identified in this study. Investigating additional environmental variables and community responses will provide a better understanding of whether and how these textured panels can contribute to improving biodiversity (species richness, Shannon diversity, and species evenness) and overall community size (total abundance) in areas requiring shoreline armoring. Additionally, research will also need to explore how these textured panels interact with other long term ecosystem functions and whether they can be effectively used in combination with other habitat enhancement strategies. Understanding these interactions will be critical for optimizing conservation and restoration efforts in freshwater environments.

Conclusion

Our study highlights the significance of eco-engineering in freshwater conservation by demonstrating how shoreline modifications can potentially influence fish community composition and species-specific habitat use. Total fish abundance and overall diversity metrics (species richness, Shannon diversity, and species evenness) did not differ significantly across shoreline treatments, although numerical differences suggested some variation among sites. Notably, 2 gamefish species, largemouth bass and smallmouth bass, were disproportionately linked to textured panels, which is encouraging considering that habitat improvement initiatives frequently target these species. However, this effect was not shown in all co-occurring species. These

findings highlight the possibility that shoreline treatments may affect age-class patterns and species distributions rather than general diversity or abundance metrics. In general, a more balanced approach to shoreline development in freshwater systems needs to be better understood. In particular, we must develop shoreline interventions that incorporate structural complexity to meet species-specific habitat requirements while also taking ecological integrity and human infrastructure demands into account. Careful consideration of design aspects, such as texture, scale, and structural complexity, can improve habitat compatibility for aquatic species in freshwater communities because coastal armouring is frequently required to prevent erosion and safeguard property.

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