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Multi-Species Fish Habitat Preferences for Various Modified Concrete Armouring Designs to Enhance Shoreline Biodiversity

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ABSTRACT

Human actions, such as the construction of concrete retaining walls as a form of shoreline armouring, pose an increasing threat to freshwater ecosystems. Conventional concrete armouring methods frequently result in habitat homogenization, which has a detrimental effect on aquatic biodiversity. This laboratory study examined the habitat preferences of four fish species (Yellow Perch [*Perca flavescens*], Bluegill [*Lepomis macrochirus*], Banded Killifish [*Fundulus diaphanus*] and Rock Bass[*Ambloplites rupestris*]) experimentally introduced to three types of concrete armouring treatment panels with different surface relief depths (5.08 cm, 7.62 cm and 10.16 cm) intended to create structural complexity paired with a flat wall control panel in 20 min dichotomous choice behavioural assays. We found that both species and treatment had a significant impact on space use, with the proportion of time spent near the different treatment panels varying among species. Compared to the treatment panels, fish spent less time near the flat control panels on average, indicating that the treatments' increased structural complexity provided more desirable habitat. Bluegill spent more time near the treatment panels than Banded Killifish and Yellow Perch, while Rock Bass spent more time near the treatment panels than Banded Killifish. As such, future efforts to implement such armouring in the field should consider using panels with a diversity of reliefs to ensure that these structures provide benefit to a wide range of fishes. Our findings highlight the possibility of using novel concrete armouring designs as alternatives to flat retaining walls to improve habitat complexity and benefit freshwater biodiversity where armouring is required.

1 | Introduction

Freshwater ecosystems provide an abundance of ecosystem services that function across local to global scales (Postel and Carpenter 1997). For example, many aquatic plants can prevent erosion and promote water purification (García-Llorente et al. 2011), while many fishes are an important source food for animals and people (Lynch et al. 2017, 2024) and provide socio-economic benefits to humanity (Lynch et al. 2016). These ecosystem services are largely supported by the biodiverse nature of freshwater systems (Lynch et al. 2023). Indeed, freshwater ecosystems house a disproportionately large fraction of the world's total biodiversity. While lakes, rivers and wetlands cover only 2.3% of the planetary surface (Lehner and Döll 2004), these ecosystems host at least 9.5% of all animal species (Balian et al. 2008). However, these ecosystems are under threat from a variety of stressors, many of which are anthropogenic (Dudgeon et al. 2006; Reid et al. 2019). As a result, freshwater ecosystems are among the most imperilled on the planet, and populations of freshwater biota have declined by more than 80% since the 1970s (WWF 2020), outpacing documented losses in most terrestrial and marine systems (Sala et al. 2000).

Many anthropogenic activities homogenize freshwater habitats and alter their structural and functional aspects (Lapointe et al. 2014), and, as a result, influence biological indicators such as species richness (Rahel 2002). One pervasive effect of human alterations to both terrestrial and riparian habitats is increased soil erosion with sediments entering aquatic systems through runoff (Borrelli et al. 2017). Both freshwater and marine systems frequently employ two similar erosion mitigation methods, namely riprap revetments and retaining walls (Chhor et al. 2020). Riprap revetments are comparatively inexpensive, require little excavation of shoreline substrate and are made up of sloped barriers of unconsolidated rock or debris that are parallel to the shoreline (Quigley and Harper 2004; Gittman et al. 2015). Traditional retaining walls, on the other hand, are cemented barriers made of stone or concrete that are perpendicular to the water line that require shoreline excavation (Gittman et al. 2015). Both approaches further alter sediment dynamics and create simplified habitats that offer reduced shelter availability and habitat connectivity (Morris et al. 2019). Typically, these modified shorelines also exhibit reduced aquatic biodiversity and abundance relative to areas with natural shorelines (Brauns et al. 2007; Gittman et al. 2016; Chhor et al. 2020). Additionally, these hard vertical structures are generally ineffective at dissipating wave energy compared to natural shorelines and shoals, resulting in increased near-bottom current velocities, flattening of the bottom substrate and changes to macrophyte diversity and abundance (Ostendorp et al. 2019; Radomski and Goeman 2001). In some cases, these novel ecosystem elements may allow invasive species to flourish (McCormick et al. 2020; Karádi-Kovács et al. 2023). The expansive network of concrete retaining walls in human-altered waterways (see Lin et al. 2020; Cooke et al. 2020) exemplifies the widespread impact of these modifications on freshwater ecosystems.

Preserving natural shorelines is critical to maintaining hydrological processes and biodiversity (Cooke et al. 2022), but there are situations where shoreline infrastructure is needed (e.g., areas with high boat traffic, high flood risk and buildings close to the shoreline). There has been an increasing effort to create or modify shoreline structures to have greater structural complexity (Francis and Hoggart 2008; O'Shaughnessy et al. 2020) with the goal of designing concrete structures that provide habitat and greater ecological functionality for promoting aquatic biodiversity (Cooke et al. 2020; Smith et al. 2020). Because of the greater structural complexity of these designs, they may also better replicate the effects of natural structures in dissipating wake and wave energy. Currently there is research being done on testing concrete panels that mimic prop root structure of mangroves (see https://www.reefwall.com/about.html; https://www.sun-sentinel.com/local/broward/fl-fake-mangroves-20161223-story.html) and on how these mangrove roots can mimic the positioning of concrete cylinders (Kazemi et al. 2018). Other efforts are underway in marine coastal areas to create 'living' armoured shorelines (Smith et al. 2020; O'Shaughnessy et al. 2020). However, the effectiveness of such innovations in freshwater ecosystems has not been well studied. To date, the only published study on this topic in a freshwater context compared how three different size classes of Bluegill (*Lepomis macrochirus*) used wall structures (fashioned out of wood and bamboo as early prototypes) with varying levels of complexity in a lab study intended to inform concrete designs (Frempong-Manso et al. 2024). There have been no assessments as yet that include multiple fish species or that actually use concrete cast panels emulating how these would actually be deployed in field settings.

There is a need to understand how different fish species use and interact with these artificial habitats to design more sustainable and ecologically friendly shoreline armouring structures. Understanding species-specific habitat preferences enables the creation of designs that support biodiversity and the health of freshwater ecosystems. While concrete armouring (e.g., retaining walls) excels in their primary role of erosion control, their ecological effects on aquatic life have raised important questions about how they influence local biodiversity. In this study, we assessed how four different species of small-bodied freshwater fishes that commonly occupy natural shorelines in littoral zones of the freshwaters of Eastern North America use different ecologically inspired designs of concrete shoreline panels relative to flat control panels. We predict that different species will interact with different treatments based on their habitat preferences, with some species favouring certain panel types over others. This semi-natural study will inform the refinement and design of shoreline panels for deployment in field settings. This unique project combines design expertise stemming from the field of architecture with knowledge of fish ecology and behaviour to evaluate this potential innovative approach to achieving conservation gains in freshwater ecosystems. The knowledge gained from this study will help inform future shoreline development design that accommodates multiple species, enhancing habitat complexity and ecological sustainability.

2 | Methods

2.1 | Study Site and Model Species

We conducted this study in a temporary wet lab constructed at the Queen's University Biological Station (QUBS) located on Opinicon Lake, Ontario, Canada, (44°34′ N, 76°19′ W) from 1 June to 31 July in 2023. Opinicon has a surface area of 889.9 ha and a maximum depth of 11 m with an average depth of 2.5 m, supporting diverse inshore fish fauna dominated by centrarchids (Keast and Harker 1977). This location offered an environment for observing fish behaviour and interactions with experimental treatments. Bluegill ($n = 80$; TL = 56–121 mm), Yellow Perch (*Perca flavescens*; $n = 80$; TL = 39–137 mm), Rock Bass (*Ambloplites rupestris*; $n = 80$; TL = 45–149) and Banded Killifish (*Fundulus diaphanus*; $n = 80$; TL = 41–82 mm) were captured using a beach seine net (5–10 mm mesh, 1.5 m high, 10 m long) in shallow waters under a scientific collection permit from the Ontario Ministry of Natural Resources and Forestry (FMZ18-Cooke-2023) and in accordance with protocols approved the Carleton University

Animal Care Committee (Cooke-UES-2023). These fish species were chosen to represent different habitat and ecological niche preferences in freshwater fish communities. Bluegill are a generalist species found in a range of habitat types, from open waters to vegetated areas (Engel 1987; Schramm et al. 1987). Rock Bass can commonly be found in rocky or weedy habitats, preferring more structured environments (George and Hadley 1979). Yellow Perch are a pelagic species and can be found in open water at varying water depths (Parker et al. 2009). Banded Killifish are often found in shallow vegetated environments (Pratt and Smokorowski 2003). This diversity in species allows us to assess how different species respond to artificial habitat complexity in the study. Once captured, all fish were measured and placed in an aerated 155 L cooler filled with lake water and transferred back to QUBS. Fish were then acclimatized for 24–72 h in one of four species-specific outdoor circular flow-through tanks (300 L), with each tank receiving an equal supply of unfiltered lake water. Behavioural assays were completed within 72 h of capture. To standardize hunger levels, fish were not fed at any point while they were in captivity.

2.2 | Treatment Types

In this study, we used four types of concrete panels (each 55.88 × 55.88 cm) with different relief depths of 0 cm (i.e., flat as control, Treatment 1), 5.08, 7.62 and 10.16 cm (Treatments 2–4, respectively). To show the various degrees of structural complexity, different relief depths were chosen, which enabled us to see the interactions between the model fish species and various surface topographies. Treatment 2 (5.08 cm relief-deep panels) offered little structural variance, simulating the tiny fissures and shallow indentations present in natural settings. Treatment 3 (7.62 cm) provided a modest level of structural complexity, akin to naturally occurring rock formations or submerged logs that give more prominent surfaces and hiding places for the growth of algae. Treatment 4 (10.16 cm) offered the maximum degree of structural complexity, replicating an approximation of woody debris habitats that can provide fish with both protection and food sources. The control (Treatment 1) lacked any relief depth, so fish behaviour could be understood by using the control panels' fully flat surface. Fish interactions with both the smooth control panels and the textured treatment panels allowed us to better understand how the ecological preferences of freshwater fish species are influenced by variations in habitat complexity.

2.3 | Habitat Panel Design and Mould Fabrication

Three variations in depth of relief for the habitat panel were produced (Figure 1). The design was computationally developed in McNeel and Associates Rhinoceros 3D modelling software ('Rhino') with a parametric modelling plugin known as 'Grasshopper'. Both Rhino and Grasshopper are widely used in various design industries to create simple and complex forms that can be developed for fabrication processes using advanced manufacturing technologies, such as additive and subtractive manufacturing. The 3D form of the panel was derived from photographs of branching patterns of woody debris found along typical lake and riverine shorelines, which provide habitat to a variety of aquatic and terrestrial species. The density and pattern of the 'branches' in the panel were developed in the 3D model to create continuity of structural ridges in the concrete material, which minimizes the need for a thick concrete backer panel, while at the same time establishing areas of relief and shelter for a variety of species. The acute angles of the branches form spaces that increase in height and depth across the panel, which offers a range of relief habitats to correspond to multiple species at differing levels of maturity. Generally speaking, the design is an attempt to rationalize the patterns of scattered and stacked woody debris into a modular and scalable habitat panel.

To create the mould for each of the three panel relief depths, the negative of each panel surface was milled into extruded polystyrene insulation foam board with a three-axis computer numerical control (CNC) mill. Foam boards were first laminated together with spray foam insulation to achieve a foam block at the required depth for each panel. The panel depth changed by increments of approximately 5.08 cm, with each variation cutting deeper into the foam board to create branches that protrude further out from the back plate. After milling the surface of the habitat panel in the foam, the outer profile of the mould was cut and then each mould thoroughly cleaned using compressed air to remove residual foam.

Specific texture on the surface of the panel was achieved through programming of the CNC mill tool path. The tool and tool path for each milling operation can be selected by the operator to achieve a wide range of surface patterns and textures. In this case, a 1.27-cm diameter rounded nose tool bit was programmed to perform parallel offset cutting across the surface stepping over by 60% of the bit diameter for each cut. This combination left residual scalloped texture across the surface of the foam board, which was then transferred to the concrete during the casting process. The surface texture was kept constant for each of the relief panels.

Once completely cut and cleaned, the foam moulds were cut into 5.08 cm wide strips that were then reassembled in the same order and secured with tape for the casting process. After some experimentation, it was discovered that these cut strips enabled an easier removal process from the concrete panel after pouring. However, the foam moulds were single use and not able to be recovered in usable form from the concrete panel once poured, despite multiple trials with various pre-applied form release agents. Concrete panels with complex relief can be produced using reusable rubber moulds. However, in this research, the foam board was a cost-effective alternative to the production of multiple costly rubber moulds for testing the different relief depths.

2.4 | Panel Assembly

Each panel was made using 1.5 bags of Quikrete concrete mixed with equal parts water to create the right consistency. The foam moulds were lined with cottle boards (Figure 2), each measuring 63.5 cm in length. The boards were held together by drilling three 10 × 8.9 cm deck screws in each corner. Concrete was then poured into the foam moulds and boards, while the concrete was being poured, someone would tap the sides of the cottle boards to remove any air bubbles. The concrete was smoothed out with a trowel, and the panels were left to dry and set for 24 h. The next

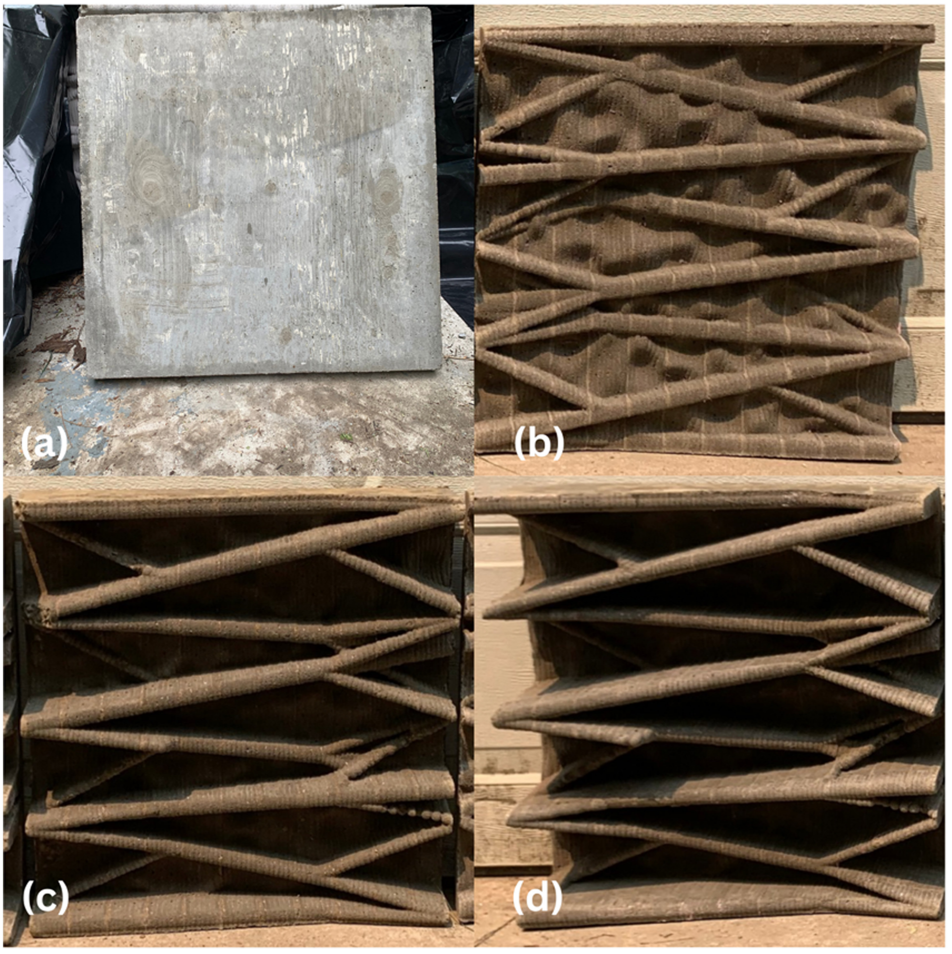

FIGURE 1 | Comparison of concrete panel treatments for fish habitat preferences. Panels were designed with varying relief depths to assess their impact on fish behaviour. (a) Treatment 1: Panels with a 5.08-cm relief depth, mimicking small crevices and shallow indentations. (b) Treatment 2: Panels with a 7.62-cm relief depth, offering moderate structural complexity like natural rock formations or submerged logs. (c) Treatment 3: Panels with a 10.16-cm relief depth, representing the highest level of structural complexity, akin to larger crevices, caves or areas under overhanging roots. (d) Control: panels with no relief depth, providing a flat surface as a baseline for comparison. Each panel measures 55.88 by 55.88 cm.

FIGURE 2 | Foam moulds used to create textured concrete panels. The moulds were secured with cottle boards to maintain their shape and integrity during the concrete pouring process.

day, the cottle boards were taken apart, and the foam moulds were removed using a crowbar. Panels were left to cure for at least 5 days prior to use.

2.5 | Behavioural Assay

To study the responses of four distinct model species to varying levels of concrete habitat relief, we employed a dichotomous choice test similar to the one used in Frempong-Manso et al. (2024). The trial arena consisted of a fibreglass raceway (85× 55× 61 cm, length × depth × width; Figure 3a,b) that was filled with ~285 L of unfiltered lakewater with a continuous flow-through supply. Treatment–control pairings were placed at both ends of the arena prior to each trial. Treatment panels were always placed on the left side of the arena and control panels were placed on the right side. In this study, we employed a double control treatment (i.e., the control on the left side was referred to as the 'treatment' in this condition). Given that the two panels are similar in nature, we predict that model species would spend equal amounts of time at each panel. By using a

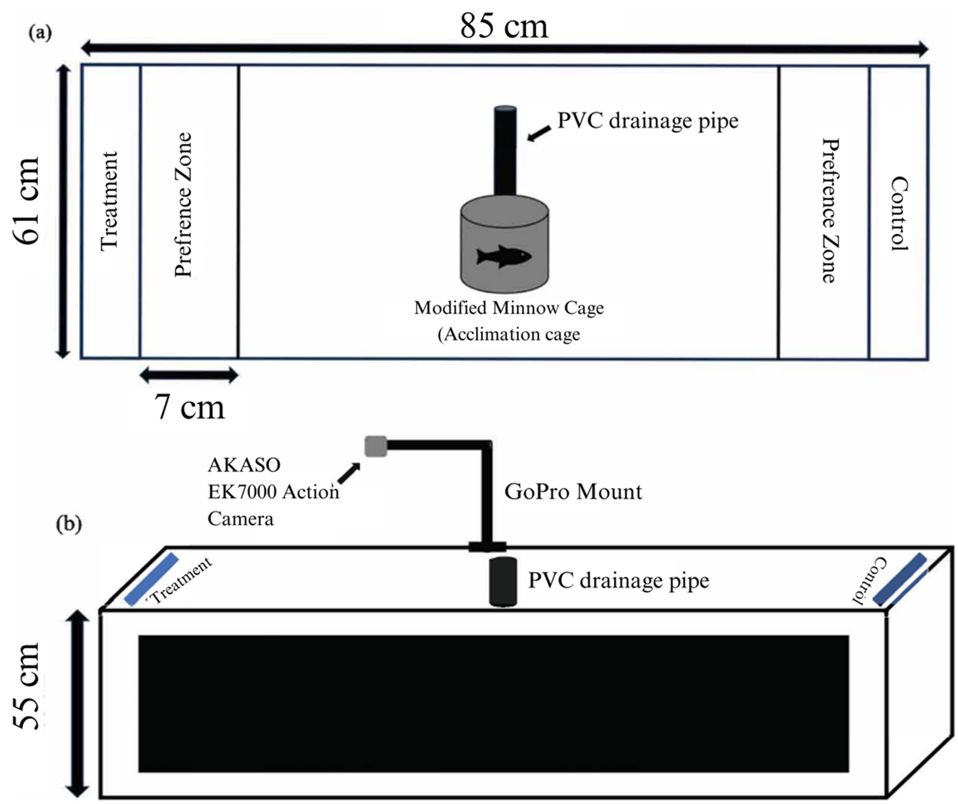

FIGURE 3 | Experimental tank setup. (a) Top view of the tank displaying preference zones, the centre acclimation cage and the treatment and control panels. (b) The tank's side view, showing the camera configuration used to capture fish behaviour.

double control treatment, we were able to better understand the spatial dynamics of the control panels, which will allow us to better comprehend fish behaviour when they are presented with distinct treatments in similar regions within the arena.

To start each trial, a focal fish was haphazardly netted out of the holding tanks and transported in a 10 L bucket for introduction to the trial arena where it was placed in a modified minnow trap (Figure 3a) and given 10 min to acclimatize. The minnow trap was removed and each fish was given 20 min to explore the arena while filmed from overhead with a digital camera (AKASO EK7000 Action Camera). The camera was mounted using a 20 cm × 20 cm plywood platform, two poles (a 122-cm pole base and a 45-cm extending out pole) and a C-clamp (Figure 3b). Each fish was used for a single trial and then released back into the lake to maintain data independence across trials. Video footage was reviewed at a later date and the following behavioural metrics were recorded: (i) the time it took to visit the treatment panel for the first time (s), (ii) the time it took to visit the control panel for the first time (s), (iii) the proportion of time spent close to the treatment panel (out of 20 min or 1200 s) and (iv) the proportion of time spent close to the control panel, where the proportions were of the 20-min (1200 s) trial lengths. A fish was considered to be near a panel and thus demonstrating a preference for it if it was within 7 cm of a panel (Auld et al. 2017). We selected this distance and the threshold as it roughly corresponded to the overall average body length of the fish utilized in this study (mean TL of 7.5 cm, SD = 1.9 cm).

2.6 | Data Analysis

Two-factorial analyses of variance (ANOVA) model was fitted for times to first visit for both the Treatment and Control panels with species and treatment (panel type) as fixed-effects factors. Similar generalized linear models (GLMs) with binomial error distributions were used to examine the proportions of time spent near a treatment panel as opposed to a control panel with the 'car' package (Fox and Weisberg 2019). Model residuals were visually assessed to confirm that the types (ANOVA or GLM) were appropriate for the different response variables. Post hoc pairwise comparisons of the estimated marginal means ('emmeans' package; Lenth 2023) was carried out using a Dunnett's adjustment to determine which particular treatments showed statistically significant variations in their effects on the response variables. All statistical tests were conducted at a significance threshold of $\alpha = 0.05$. Data figures were generated with 'ggplot2' (Wickham 2016), 'viridis' (Garnier et al. 2023), and 'cowplot' (Wilke 2020). All statistical analyses were performed using R version 4.3.0 (R Core Team, 2022).

3 | Results

Species ($p < 0.001$) and Treatment ($p = 0.0425$), but not their interaction (Table 1), significantly influenced the length of time it took for fish to make their initial visits to the treatment panels in dichotomous choice tests. It was observed that certain species visited panels with more depth relief more quickly than those without, suggesting that they preferred these intricate designs (Table 1). For control panels, Species ($p<0.0001$) had a significant effect on the time taken for initial visits but neither Treatment ($p=0.173$) nor the interaction between Species and Treatment did ($p=0.719$; Table 1). This suggests that the differences in relief in the treatment panel types influenced the time it took species to approach them, while control panels were visited after similar intervals when paired with identical treatments. The control panels were not assigned to a specific treatment but were used as a baseline comparison against paired treatment panels. In general, it took fish longer to visit control panels than

TABLE 1 | ANOVA and GLM results for the effects of Species, Treatment and their interaction on times to first visit and proportion of time spent near different treatment panels by four focal species.

Response	Model term	df	Statistic	p
Time to first treatment panel visit (s)	Species	3, 277	$F=5.745$	<0.001
	Treatment	3, 277	$F=2.762$	0.0425
	Species:Treatment	9, 277	$F=1.500$	0.148
Time to first control panel visit (s)	Species	3, 239	$F=9.302$	<0.0001
	Treatment	3, 239	$F=1.677$	0.173
	Species:Treatment	9, 239	$F=0.688$	0.719
Proportion of time at treatment	Species	3, 275	$\chi^2=52.489$	<0.0001
	Treatment	3, 275	$\chi^2=25.302$	<0.0001
	Species:Treatment	9, 275	$\chi^2=21.086$	0.0123
Proportion of time at control	Species	3, 275	$\chi^2=67.078$	<0.0001
	Treatment	3, 275	$\chi^2=8.640$	0.0345
	Species:Treatment	9, 275	$\chi^2=13.603$	0.137

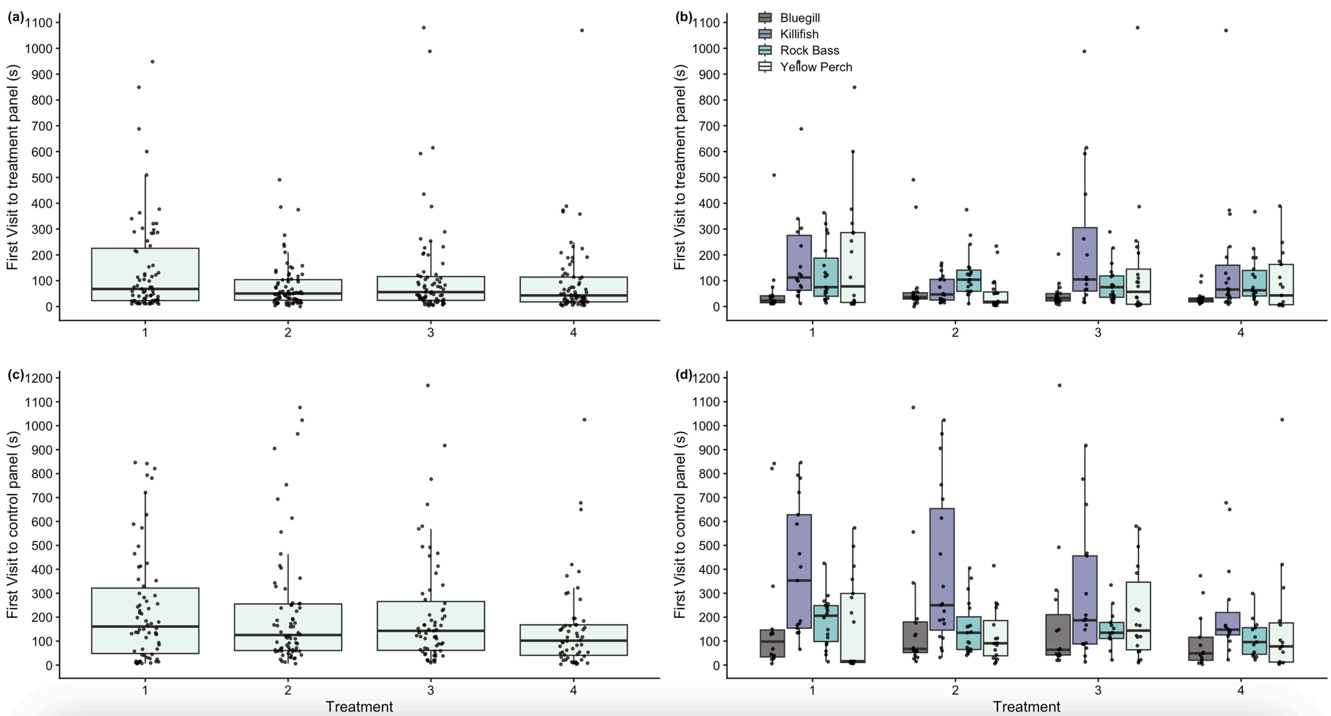

FIGURE 4 | Distribution of time to first visit to panels by treatment and species. (a) The distribution of time to first visit to treatment panels (in seconds) across different treatment conditions. Each boxplot represents a treatment level, with jittered points indicating individual data points. Treatment 1 corresponds to the control panel, Treatment 2 represents panels with a 5.08-cm relief depth, Treatment 3 represents panels with a 7.62-cm relief depth and Treatment 3 represents panels with a 10.16-cm relief depth. (b) Distribution of time to first visit to treatment panels across various treatment conditions and species. Each boxplot represents a treatment group, with box colour indicating species categories. (c) Distribution of time to first visit to control panels (in seconds) across different treatment conditions. (d) Distribution of time to first visit to control panels across various treatment conditions and species.

treatment panels (Figure 4a,c) with Bluegill consistently demonstrating the shortest initial visit times than the three other focal species (Figure 4b,d).

Fish species had a significant effect on the proportion of time spent near treatment panels ($p < 0.0001$), as did Treatment ($p < 0.001$), and the interaction between Treatment and Species ($p = 0.0123$; Table 1). In general, fish spent the most time near Treatment 4 (Figure 5a) and Bluegill tended to spend more time at the treatment panels than the other species, with Banded Killifish and Yellow Perch spending the least time (Figure 5b). Post hoc pairwise comparisons revealed differences in species preferences, with Bluegill spending a greater proportion of time near the panels than Banded Killifish ($p < 0.0001$) and Yellow Perch ($p = 0.0004$), while there were no differences between Bluegill and Rock Bass ($p = 0.260$). Rock Bass spent more time near treatments compared to Banded Killifish ($p < 0.0001$), while Yellow Perch spent more time near the treatment panels compared to Banded Killifish ($p = 0.041$). Rock Bass vs. Yellow Perch ($p = 0.113$) showed no difference in the proportion of time spent near the treatment panel (Table 2).

For the control panels, both Species ($p < 0.001$) and Treatment ($p = 0.034$) significantly affected the proportion of time spent near the control panels. However, the interaction between Species and Treatment ($p = 0.137$) was not significant (Table 1). Fish behaviour in the double control treatment (i.e., two controls, and one control is considered a 'treatment') confirmed the validity of this method to evaluate baseline spatial preferences, showing that time spent close to control panels was distributed fairly evenly when paired with identical controls. To create a baseline comparison for spatial preferences, one identical control panel is arbitrary labelled as a 'treatment' in the double control setting up. This arrangement makes sure that variations in fish behaviour close to these similar panels reflect spatial distribution rather than inherent panel properties. Fish of all species tended to spend larger proportions of time near the control panels with an apparent stepwise decrease in proportion with increasing surface complexity of the treatment panels (Figure 5c). Banded killifish spent the least time near the control panels, and the other three species demonstrated similar responses to the Control and the two lower-relief treatments. Bluegill spent considerably less time near control panels when they were paired with Treatment 4 (Figure 5d). Bluegill spent more time overall near the control panels than both Banded Killifish ($p < 0.0001$) and Rock Bass ($p = 0.014$), but no significant difference was observed between Bluegill and Yellow Perch ($p = 0.818$). Yellow Perch spent more time near control panels than Banded Killifish ($p < 0.0001$), while Rock Bass spent more time near control panels than Banded Killifish ($p = 0.007$) and Yellow Perch ($p = 0.0005$; Table 2).

4 | Discussion

Understanding the habitat preferences of freshwater fish species will be important for developing effective conservation and habitat restoration strategies (Roni et al. 2014). In this study, we investigated the habitat preferences of four model freshwater fish species

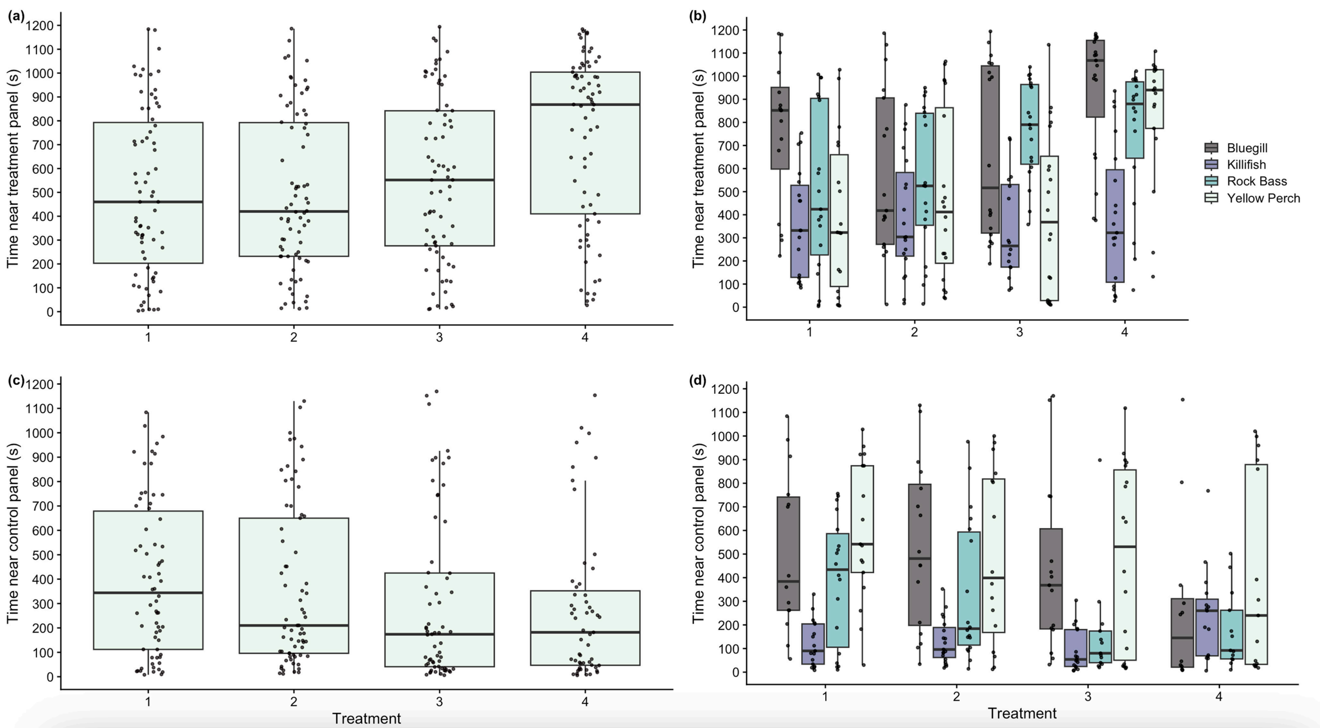

FIGURE 5 | Proportion of time spent near panels by treatment and species. (a) The proportion of time near treatment panels (in seconds) across different treatment conditions. Each boxplot represents a treatment level, with jittered points indicating individual data points. (b) Distribution of time spent near the treatment panels across various treatment conditions and species. Each boxplot represents a treatment group, with box colour indicating species categories. (c) Distribution of time near control panels (in seconds) across different treatment conditions. (d) Distribution of time spent near the control panels across various treatment conditions and species. Treatment 1 corresponds to the control panel, Treatment 2 represents panels with a 5.08-cm relief depth, Treatment 3 represents panels with a 7.62-cm relief depth, and Treatment 4 represents panels with a 10.16-cm relief depth.

TABLE 2 | Estimated marginal means for the proportion of time model species spent near the treatment or control panels across different panel combination.

	Contrast	Estimate	SE	z-ratio	*p*
Treatment	Bluegill—Killifish	1.279	0.200	6.401	< 0.0001
	Bluegill—Rock Bass	0.349	0.191	1.827	0.2607
	Bluegill—Yellow Perch	0.766	0.191	4.001	0.0004
	Killifish—Rock Bass	−0.929	0.195	−4.773	< 0.0001
	Killifish—Yellow Perch	−0.513	0.195	−2.635	0.0418
	Rock Bass—Yellow Perch	0.416	0.186	2.237	0.113
Control	Bluegill—Killifish	1.472	0.249	5.913	< 0.0001
	Bluegill—Rock Bass	0.653	0.218	2.994	0.0146
	Bluegill—Yellow Perch	−0.174	0.199	−0.874	0.818
	Killifish—Rock Bass	−0.820	0.257	−3.186	0.0079
	Killifish—Yellow Perch	−1.647	0.242	−6.816	< 0.0001
	Rock Bass—Yellow Perch	−0.827	0.210	−3.947	0.0005

(i.e., Banded Killifish, Bluegill, Rock Bass and Yellow Perch) when exposed to concrete panels with varying habitat relief depths. The findings demonstrated that, although the fish's reactions to the various relief depths were somewhat comparable, each species' interactions with these treatments differed noticeably. The variation that we observed highlights the importance of considering species-specific preferences when designing artificial habitats.

Species-specific behavioural patterns were observed during the length of time it took for fish to first visit the treatment panels, suggesting that species exhibit varying levels of exploratory behaviour or habitat preferences. While the type of treatment impacted first visit times, the interaction between treatment and species was not significant. That finding suggests that while each species had a different response to the treatments, the responses were not driven by relief depth, species or a combination of the two. We did not observe any significant effects on first visit time when comparing treatment and control panels, with species being the primary determinant. This suggests that the complexity of the treatment panels did not selectively attract fish to the control panels, further emphasizing the role of the control design used in this study.

Species, treatment (panel type), and the interaction between species and treatment were significant factors on the proportion of time spent near treatment panels. Bluegill spent a higher proportion of time near treatment panels compared to Yellow Perch and Banded Killifish, whereas Banded Killifish spent less time near treatment panels than Rock Bass and Yellow Perch. These differences can be explained by habitat preferences; Bluegill are often found in vegetated habitats (Engel 1987; Schramm et al. 1987), and may have been more drawn to certain treatment panels that mimicked these environments. In contrast, Banded Killifish are found in open or less vegetated habitats (Brind'Amour et al. 2005; Pratt and Smokorowski 2003) and accordingly were less inclined to spend time near the treatment panels. We observed no significant differences between Rock Bass and Bluegill, possibly due to overlapping habitat preferences given that they are confamilials. For the control panels, species and treatment type significantly influenced the proportion of time spent near the control panels; however, their interaction was not significant. This finding suggest that despite certain species interacting differently with the control panels, the interactions were independent of treatment type. Notable differences were observed between Yellow Perch and Banded Killifish, compared to Bluegill, reinforcing the notion that habitat preferences are driving these behaviours.

The two panel types with the greatest habitat depth reliefs (7.62 cm and 10.16 cm, Treatments 3 and 4) were highly preferred by Banded Killifish and Bluegill. This preference can potentially be explained by their ecological roles: relief depths allow for greater surface area for periphyton growth providing a food source and improved predator protection (Verdonschot et al. 2012; Gotceitas and Colgan 1987), which aligns with the natural tendency of Bluegill and Banded Killifish to inhabit structurally complex and vegetated environments (Keast 2020). Rock Bass and Yellow Perch on the other hand showed more versatility, preferring a range of relief depths. This reflects their broad habitat preferences: Rock Bass are ambush predators that can do well in both structured and open habitats (Jacobus and Webb 2005), whereas Yellow Perch are opportunistic feeders capable of adapting to a variety of habitat conditions (Keast 2020). In this regard, it appears that artificial habitats that incorporate both high and low relief structures can support species with specific preferences such as Bluegill and Banded Killifish, and generalist species like Rock Bass and Yellow Perch.

The ecologically inspired concrete panels tested here mimic key aspects of natural environments, which has the potential to provide shelter and foraging opportunities. These benefits may extend beyond individual species to support other ecological interactions, which are critical to the maintenance of a robust and well-balanced aquatic environment (Kovalenko et al. 2012). For example, complex structures could be incorporated into stabilization initiatives to improve habitat quality and reduce the detrimental effects of erosion. Conventional techniques for stabilizing shorelines frequently produce habitats that are homogeneous and less conducive to biological life (Hendon et al. 2000). On the other hand, intricate concrete panels have the potential to offer the shoreline both structural stability and biological advantages, such as increased habitat availability and improved water quality through the filtration services provided by organisms colonizing these structures (sensu Way et al. 1995).

Despite the promising results, the study has limitations. All the experiments conducted in this study were done in a controlled lab environment, and while it was important to eliminate extraneous variables, this may limit the generalizability of the findings to real-world dynamics such as hydraulic variability or geotechnical stability. Turbulent flow conditions, sediment transport and long-term material durability remain untested, limiting the applicability of these findings to natural freshwater systems. There are many other proximate cues for habitat selection, including velocity and light that were not studied in this study and more research will be needed on how environmental variables impact habitat selection. Testing additional fish species and incorporating interspecific interactions, such as competition and predation, would also enhance understanding of ecological processes in artificial habitats. Additionally, it is important to acknowledge that the treatment design for this study primarily focused on depth of crevices, repeated in a distinct pattern and that spatial measures (e.g., topography, heterogeneity, proportion of crevices per cm^2) were not measured yet, those factors could also influence how fishes interact with panels. This study was designed to inform field deployments, building upon the earlier laboratory studies that used wood and bamboo designs (i.e., Frempong-Manso et al. 2024). Although the panels in our study were composed entirely of concrete, alternative materials could be explored in tandem with or without concrete to further diversify the habitat panels and create more suitable conditions for species that avoid purely hardened surfaces. The incorporation of softer materials could also lend itself to supporting a diverse invertebrate community, thus impacting the interactions of other species.

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Ethics Statement

The Carleton University Animal Care Committee approved of all experimental methods, which were conducted in compliance with the guidelines established by the Canadian Council on Animal Care. (Animal Use Protocol no. 104281).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data has been made available publicly on Figshare. Citation: Frempong-Manso, Acacia (2025). Supplementary data and R code for ‘Multi-Species Fish Habitat Preferences for Various Modified Concrete Armoring Designs to Enhance Shoreline Biodiversity’.csv. figshare. Dataset. https://doi.org/10.6084/m9.figshare.28811570.v1.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

We declare that during the preparation of this work that no generative AI or AI-assisted technologies were used. We take full responsibility for the content of the publication as authors of the text.

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Supporting Information

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