Environ Biol Fish
https://doi.org/10.1007/s10641-024-01568-5

Informing the design of fish-friendly shoreline retaining walls for freshwater systems

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Received: 27 December 2023 / Accepted: 17 June 2024

Abstract The structural complexity of aquatic habitats is often reduced by the installation of retaining walls designed to stabilize shorelines and decrease erosion. Alternative armoring techniques such as wall panels that imitate natural habitat complexity are being developed, but they require knowledge of how different structural elements are used by fishes with varied body sizes. In this study, we examined the effects of incorporating four distinct habitat features and textures into experimental retaining wall panels on the behavior of bluegill (*Lepomis macrochirus*) across a range of body sizes, in comparison to a control (plain) panel. The proportion of times that fish spent near the treatment panels generally increased with panel complexity but there was variation among fish size classes, with larger bluegill preferring medium complexity structure and smaller bluegill preferring the greatest level of complexity. We did not observe any differences in times to visit the panels between treatments or size classes. These findings will help inform and refine the design of retaining walls, providing structural habitat complexity to benefit freshwater fishes across a range of body sizes and life history stages.

Keywords Shoreline alteration · Fish habitat · Animal behavior · Erosion control

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10641-024-01568-5.

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Introduction

Over the past few decades, freshwater biodiversity has experienced a significant decline due to human impacts on the environment (Harrison et al. 2018). Extensive physical modifications to natural ecosystems have resulted in substantial losses of biodiversity across geographic scales (Vitousek et al. 1997). Since the 1970s, freshwater biodiversity has declined more rapidly than marine and terrestrial environments, with one-third of freshwater species facing the threat of extinction (Collen et al. 2014; Harrison et al. 2018). Despite freshwater ecosystems constituting less than 1% of the planet's surface, they host 10% of animal species (Dijkstra et al. 2014; Strayer and Dudgeon 2010). The five main stresses that humans impose on freshwater ecosystems are overexploitation,

Published online: 15 July 2024

introduction of invasive species, habitat degradation, altered water flow, and pollution (Dudgeon et al. 2006). Nevertheless, despite Dudgeon et al.'s (2006) "call to arms," nothing has changed. More recently, Reid et al. (2019) identified twelve distinct intensified pressures, including harmful algal blooms, temperature changes, calcium depletion, cumulative stressors, salinization of freshwater, invasions and e-commerce, growing hydropower, microplastic pollution, noise and light pollution, emerging contaminants, infectious diseases, and engineered nanomaterials. Of the factors mentioned above, habitat alteration has been identified as a primary cause of population declines in freshwater ecosystems (WWF 2016).

To counteract shoreline erosion and safeguard critical riparian infrastructure, various approaches have been implemented including the installation of retaining walls and other shoreline armoring methods (Cooke et al. 2020). Conventional shoreline armoring methods frequently feature concrete or steel retaining walls to mitigate erosion of both natural and infilled sites. A number of structural elements of aquatic systems are altered by anthropogenic activity, including the size and homogeneity of substrate particles, the quantity and composition of shoreline habitat, including woody debris (Christensen et al. 1996), and the composition and density of macrophytes (Bryan and Scarnecchia 1992). Runoff of nutrients, sediments, organic matter, and pollutants from human activities alters the landscape throughout watersheds, affecting water quality. While there has been a great deal of research on fish-habitat linkages in streams (Angermeier and Karr 1984; Gorman and Karr 1978; Schlosser 1982), comparatively little is known about the ecological effects of physical habitat modifications in lakes.

Freshwater habitat modifications often lead to decreased structural complexity, which can have different types of adverse effects on aquatic animals. For example, rigid shoreline structures frequently impose obstacles to ecological connectivity, hindering the establishment of diverse and resilient freshwater communities (Morris et al. 2019). Consequently, there is a growing imperative to reassess construction materials to mitigate the environmental repercussions of such developments (Horvath 2004; Kibert 2016). The dynamics between human activities and ecosystems necessitate re-evaluation (Johnson et al. 2017), particularly regarding the use of materials like concrete. For example, retaining walls employed for coastal defense against erosion and flooding may unintentionally alter littoral environments and compromise near-shore biodiversity (Chhor et al. 2020).

While preserving natural shorelines is the ideal approach, situations may arise where this is not feasible (e.g., in areas with high boat traffic where shorelines could be eroded rapidly). Consequently, there is growing interest in adapting concrete designs to enable biodiversity recoveries in freshwater systems. Recent research has unveiled the potential of engineering concrete shorelines to incorporate natural forms that foster ecological functions and habitat creation (Cooke et al. 2020). Integrating natural forms drawing inspiration from mangrove trees has already yielded promising outcomes in coastal regions (visit https://www.reefwall.com/about.html for details). These adapted concrete designs offer intricate habitats for aquatic life while also demonstrating the potential to dissipate wave and wake energy similar to the mangroves they are patterned after. Nonetheless, the applicability and effectiveness of similar designs in freshwater systems represents an important research gap.

The significance of fish body size in habitat selection arises from the inherent disparities in resource utilization, foraging techniques, and predator–prey dynamics between size classes (Woolnough et al. 2009) that result in different habitat interactions within one species in the same ecosystem. For instance, smaller fish are often more susceptible to predation and may seek refuge in microhabitats offering concealment, such as submerged vegetation or complex structures (Savino and Stein 1989). In contrast, larger fish may require or prefer more open and low-complexity habitats to facilitate efficient foraging and other fitness-related activities (Savino and Stein 1989). Fishes often undergo various ontogenetic changes during their early life stages associated with enhanced feeding capabilities and fortifying defenses against competitors and predators (Bailey 1994). Broadly coinciding with these ontogenetic changes, many fish species relocate from their nursery habitats to environments more suitable to their requirements as adults (Eggleston 1995). Innovative shoreline designs could potentially serve as artificial habitats, offering a place for juvenile fish undergoing these crucial ontogenetic shifts, or perhaps aid in facilitating the transition of fish to their preferred environments, amplifying their ability to adapt and thrive.

To identify opportunities for enhancing shoreline erosion controls and achieving conservation gains in freshwater systems, our objective was to deepen our comprehension of the vertical wall habitat complexity preferences of bluegill (*Lepomis macrochirus*) as a model species. By testing non-conventional erosion control designs integrating natural habitat forms, we sought to ascertain how different sizes of bluegill respond to varying levels of habitat complexity and determine whether such designs can effectively support diverse fish species assemblages, thereby contributing to the overall health and resilience of freshwater ecosystems. Furthermore, our investigation intends to explore whether distinct sizes of bluegill exhibit preferences for specific textures and structures. The outcomes of this study not only enhance our understanding of bluegill habitat preferences but also offer insights into the potential conservation benefits attainable through the modification of retaining walls in freshwater systems.

Methods

Study location and species

Opinicon Lake (Chaffey's Lock, Ontario, Canada, 44°33′53″N 76°19′33″W) Is part of the Rideau Canal Navigational Channel within the Rideau Lakes watershed in eastern Ontario, Canada.. This watershed is a popular location for recreational fishing, and the area is home to several commercial fisheries.

bluegill are widely distributed and extensively dispersed in lotic and lentic freshwater systems in North America (Whitten et al. 2020), making them a logical study species to test the influence of habitat complexity on fish habitat preferences. Their prevalence in these ecosystems underscores their significance as a food source for various other aquatic species (Azuma and Motomura 1998), making them a crucial group to consider supporting with artificial habitats. bluegill ($n = 300$; TL = 25–203 mm) were obtained from Opinicon Lake between July 1 and July 15, 2022. Small (ranging from 25 to 50 mm) and medium-sized (ranging from 76 to 127 mm) fish were collected from shallow habitats using a beach seine (5–10 mm mesh, 1.5 m height, and 10 m length), and large fish (ranging from 152 to 203 mm) were angled in deeper water using size 2 circle hooks baited with sections of live earthworm (*Lumbricus* sp.). We note that if our sampling may have been skewed or biased, it was tied to size class from using two discrete capture methods.

As soon as fish were caught, all the fish were measured and placed in a 155 L aerated plastic cooler filled with lake water. The bluegill were then immediately moved to Queen's University Biological Station (Chaffey's Lock, Ontario, Canada) and housed for 24–72 h in outdoor circular flow-through tanks (300 L) supplied with unfiltered lake water (DO > 90% saturation; 24–26 °C) under ambient light conditions. To standardize hunger levels, fish were not fed at any point while they were in captivity. All experimental procedures were carried out in accordance with the standards defined by the Canadian Council on Animal Care and with the approval of the Carleton University Animal Care Committee (Animal Use Protocol no. 104281).

Behavioral testing

We used a dichotomous choice test like that described in Auld et al. (2017); however, instead of looking at mate choice, we examined bluegill preferences for different textures and structures of retaining walls at either end of a trial arena consisting of a fiberglass raceway (Fig. 1a, b; 85 cm length × 61 cm width × 55 cm depth, giving it an approximate total volume capacity of 285,425 cm^3 (or 285,175 L). Before each trial, we equipped each end of the arena with panels presenting treatment–control combinations. Treatment panels were always placed on the left side of the arena, while the controls were placed on the right. We used a double control treatment, which consisted of one control on each side (i.e., left and right) with the control on the left designated as the "treatment." We assumed that bluegill would spend equal time on both sides due to their identical nature. Having a double control allowed us to better understand the spatial dynamics of control usage, which would ultimately facilitate a better understanding of how fish behavior varied when confronted with different treatments situated in analogous spaces within the arena.

Treatment 1 (Fig. 2a) consisted of a 61 cm by 58 cm plain panel of plywood; with the edges

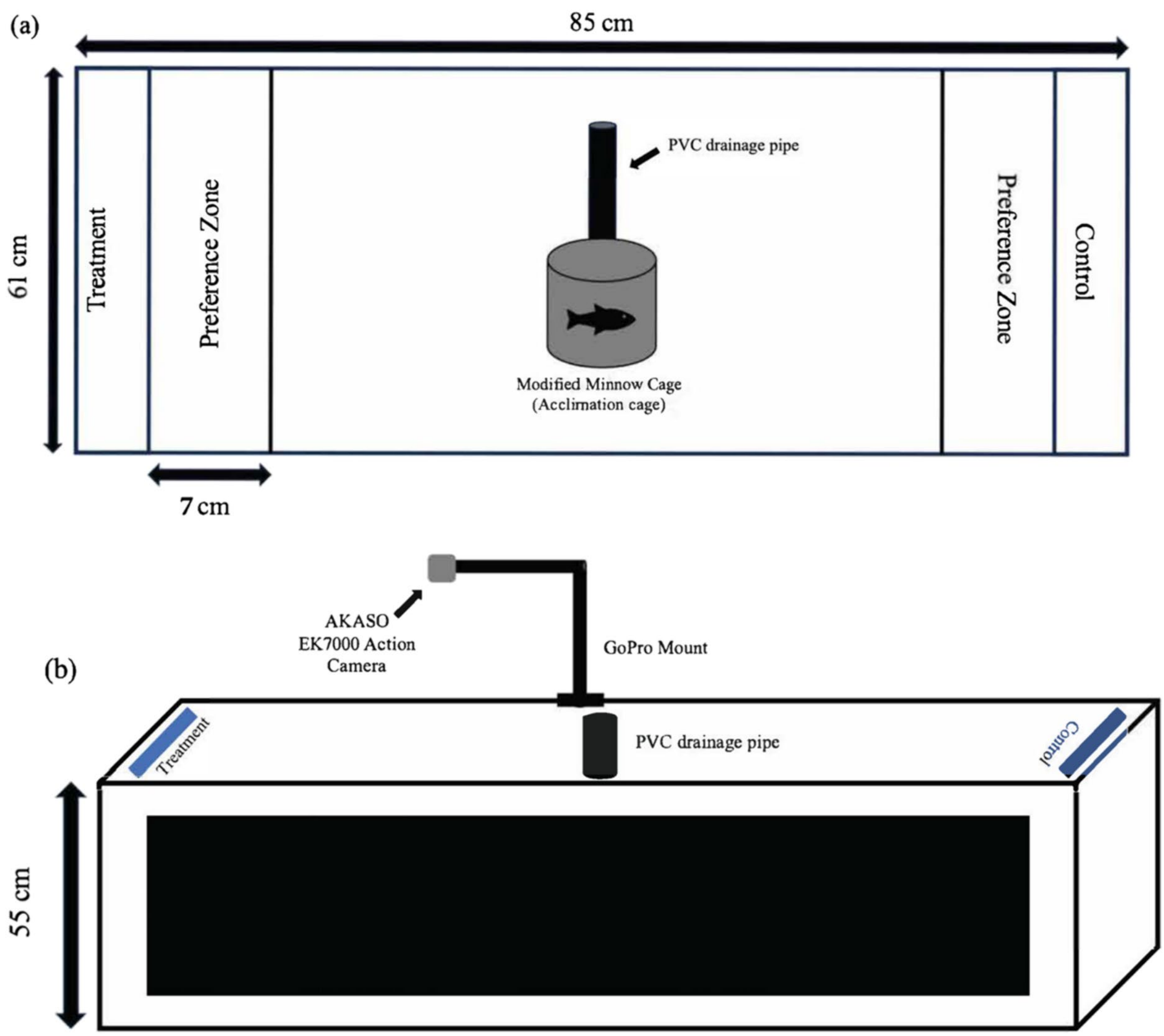

Fig. 1 Experimental setup for investigating bluegill preferences in a fiberglass raceway trial arena. **a** The trial arena, measuring 85 cm in length, 61 cm in width, and 55 cm in depth, featured retaining walls with different textures and structures at either end. **b** Cameras were strategically mounted using a C-clamp affixed to two poles (122 cm base and 45 cm extending out pole) with a 20 cm × 20 cm plywood base to capture behavioral responses. A modified minnow trap was used for acclimating the focal fish, which were then given 20 min to explore the arena. Video data was recorded using the AKASO EK7000 Action Camera

tapered off and rounded to serve as a control. Treatment 2 (Fig. 2b) consisted of six vertical bamboo poles with a 2-inch diameter that are spaced out 152 mm apart. Treatment 3 (Fig. 2c) consisted of two layers of bamboo; the first layer of bamboo consisted of six bamboo poles that were placed vertically; and the second layer had three bamboo poles that formed a zig-zag pattern. Treatment 4 (Fig. 2d) consisted of four layers of bamboo; the first layer had six vertical bamboo poles; the second layer had three bamboo poles that form a zig-zag pattern; and the third layer had four vertical bamboo poles; and the fourth layer had three bamboo poles that form a zig-zag pattern. Treatment 5 (Fig. 2e) consisted of six horizontal bamboo poles. To test the different levels of habitat complexity, we selected bamboo as it allowed for control over spatial arrangement and structural variation, which allowed us to isolate the

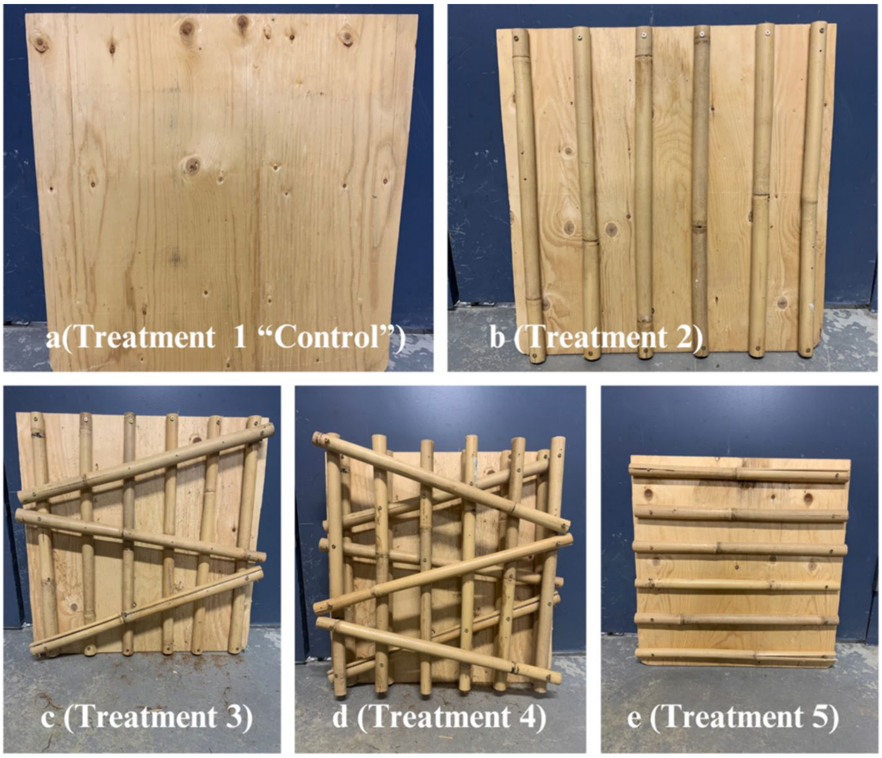

Fig. 2 Model retaining walls for habitat preferences of bluegill (*Lepomis macrochirus).* Each trial involved equipping one end of the arena with a control panel and the other end with one of the four treatment panels. In control trials, two control panels were placed in the arena

effects of habitat complexity on bluegill behavior. While the bamboo structures were simplified treatments, the designs are meant to reflect the natural forms (e.g., vegetation, submerged branches) that bluegill encounter in their natural habitats. Bamboo structures would inform the development of future molds for concrete or other more robust materials.

Unfiltered surface-drawn lake water was continuously supplied to the flow-through arenas that were emptied and cleaned as needed. Each trial began with the transfer of a focal fish from the holding tank to a 10 L bucket filled with lake water for transport to the trial arena, where the fish was placed under a modified minnow trap (see Fig. 1a) and given 10 min to acclimate to the arena before the trap was lifted. The behavioral trials lasted a total of 20 min, during which the fish were able to freely investigate the arena, and data was collected via video recordings. To ensure independence of data across trials, each fish was used for a single trial only and released back into the lake afterwards. To record the trials, cameras (AKASO EK7000 Action Camera) were mounted with a C-clamp using two 122 cm (pole base) and 45 cm (extending out pole) poles and a 20 cm × 20 cm plywood base (Fig. 1b).

Video footage were reviewed later to record the following behavioral metrics: (i) time to first visit to the treatment panel; (ii) time to first visit to the control panel; (iii) proportion of time spent near the treatment panel; and (iv) proportion of time spent near the control panel. Fish were scored as demonstrating a "preference" for a panel type when they were within 7 cm of it (Auld et al. 2017). We chose to use 7 cm as it approximated the average body length of fish used in our study (mean TL of 114 mm, SD = 51.38 mm). Using this distance provides a conservative estimate of preference as it required close physical proximity to the panel. We selected the above metrics based on their relevance to us gaining a better understanding of the habitat preference and utilization of treatments in this study.

Statistical analysis

Statistical analysis was performed using R version 4.3.0 (R Core Team, 2022) to investigate the effects of different treatments on bluegill behavior. First, two separate two-way factorial analysis of variance (ANOVA) models were fitted, one for the first visit to the Treatment panel and one for the first visit to the Control panel. Next, GLM models were run to determine the proportion of time spent near treatment or control panels. Post hoc pairwise comparisons of estimated marginal means were conducted using a Dunnett's adjustment test was used to determine the specific treatments that exhibited statistically significant differences in their effects on the response variables. The assumptions of the ANOVA models, including normality homoscedasticity of residuals, were checked to ensure the validity of the results. The following R packages were used: "mvtnorm" (Genz and Bretz 2009), "survival" (Therneau 2023), "TH.data" Hothorn T. (2023), "MASS" (Venables and Ripley 2002), and "emmeans" (Lenth 2023). All statistical tests were performed at a significance level of $\alpha = 0.05$, and the results were reported with their corresponding p-values to determine the significance of the effects. To create the figures, we used the R packages "ggplot2,"(Wickham 2016) "viridis"(Garnier et al. 2023), "viridisLite" (Garnier et al. 2023), and "cowplot" (Wilke 2020) .

Results

Body size ($p = 0.828$; ANOVA, $F = 0.189$) and the interaction between body size and treatment ($p = 0.518$; ANOVA, $F = 0.899$) was not significant, but rather treatment type had a significant impact on how long it took bluegill to visit the treatment panel for the first time ($p = 0.009$; ANOVA, $F = 3.410$; Fig. 3; Table 1). Neither body size ($p = 0.625$; ANOVA, $F = 0.471$) nor treatment ($p = 0.916$; ANOVA, $F = 0.239$) showed statistically significant effects during the initial visit to the control panel (Fig. 3 and Table 2), nor were they significantly impacted by the interaction between body size and treatment ($p = 0.295$; ANOVA, $F = 1.207$; Fig. 4).

Treatment type significantly affected the proportion of time spent near the treatment panels ($\chi^2 = 127.71$, df $= 4$, $p < 0.001$. The Control (Treatment 1) differed significantly from Treatment 3,

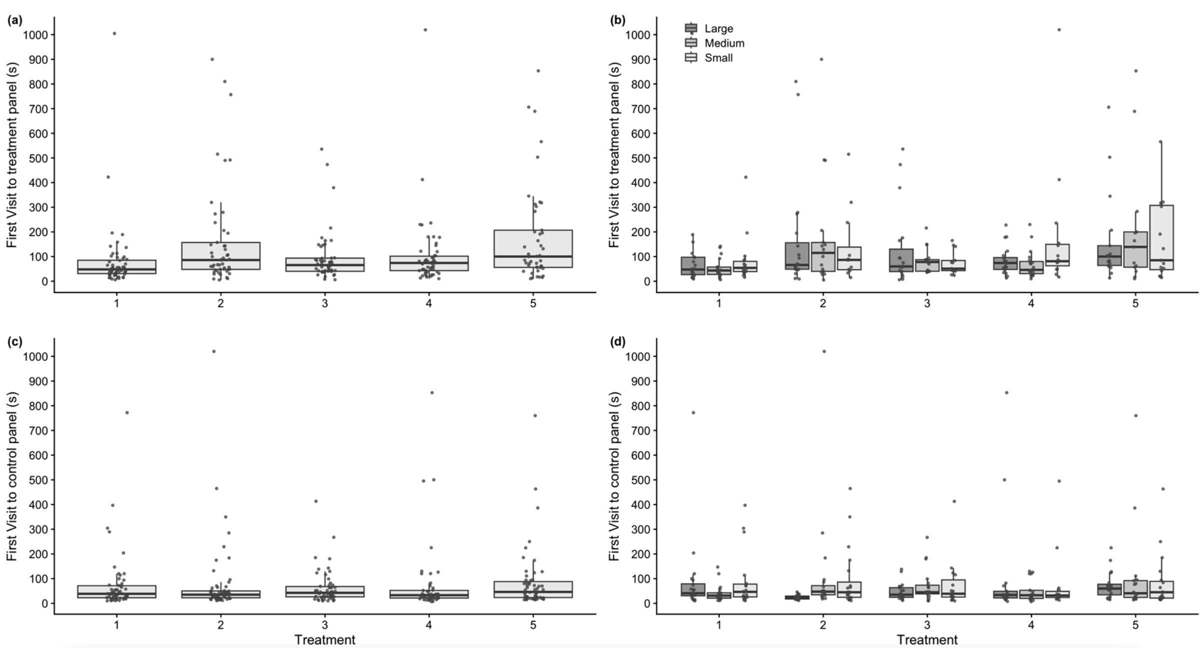

Fig. 3 **a** The distribution of time to first visit to treatment panel(s) (in seconds) across different treatment conditions. Each boxplot represents a treatment level, with jittered points indicating individual data points. **b** Distribution of time to first visit to treatment panel across various treatment conditions and sizes. Each boxplot represents a treatment group, with box color indicating size categories. **c** Distribution of time to first visit to control panel(s) across different treatment conditions. **d** Distribution of time to first visit to control panel(s) across various treatment conditions and sizes

Table 1 Analysis of variance (ANOVA) results for the effects of size, treatment, and their interaction on time to first visit to the treatment panels by bluegill

Source	Df	Sum Sq	Mean Sq	F value	Pr(> F)
Size	2	10215	5107	0.1893	0.8277
Treatment	4	368075	92019	3.4100	0.0098**
Size:treatment	8	194138	24267	0.8993	0.5177
Residuals	239	6449369	26985		

Table 2 Analysis of variance (ANOVA) results for the effects of size, treatment, and their interaction on time to first visit to the control panels by bluegill

Source	Df	Sum Sq	Mean Sq	F value	Pr(> F)
Size	2	15169	7584.5	0.4713	0.6247
Treatment	4	15440	3860	0.2399	0.9156
Size:treatment	8	155395	19424.4	1.2071	0.2950
Residuals		4151706	16091.9		

which consisted of a vertical and horizontal bamboo design (estimate = −0.939, p = 0.0001) and Treatment 4 a multi-layered bamboo design (estimate = −1.869, p < 0.0001), but not from Treatment 2 a vertical bamboo design (estimate = 0.326, p = 0.6539) or Treatment 5 a horizontal bamboo design (estimate = −0.422, p = 0.3229; Table 3). This suggests that the specific habitat complexities of Treatments 3 and 4 appear to be more attractive to bluegill compared to the other treatments in terms of the proportions of time spent near the panel.

Treatment type significantly affected the proportion of time spent near the control panels (χ^2 = 35.121, df = 4, p < 0.001). The Control (Treatment 1) differed significantly from Treatment 2 (estimate = −1.027, p < 0.0001), but not from Treatment 3 (estimate = −0.510, p = 0.1507), Treatment 4 (estimate = 0.141, p = 0.9768), or Treatment 5 (estimate = −0.450, p = 0.2519; Table 4). This suggests that Treatments 2 and 4 are impacting the proportion of time bluegill spend near the Control panel.

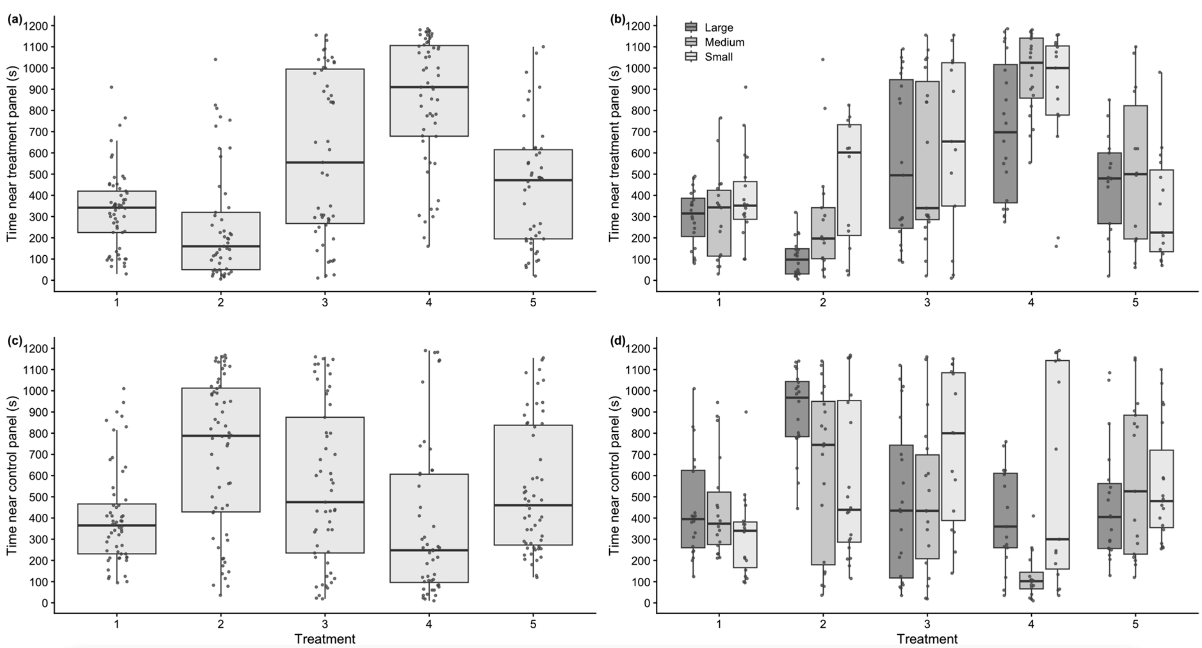

Fig. 4 **a** The proportion of time near treatment panel(s) (in seconds) across different treatment conditions. Each boxplot represents a treatment level, with jittered points indicating individual data points. **b** Distribution of time spent near the treatment panel(s) across various treatment conditions and sizes. Each boxplot represents a treatment group, with box color indicating size categories. **c** Distribution of time near control panel(s) across different treatment conditions. **d** Distribution of time spent near the control panel(s) across various treatment conditions and sizes

Table 3 Estimated marginal means for the proportion of time bluegill spent near the treatment panel across different treatments

Contrast	Estimate	SE	df	z-ratio	*p*-value
Treatment 1—Treatment 2	0.326	0.240	Inf	1.359	0.6539
Treatment 1—Treatment 3	−0.939	0.214	Inf	−4.396	0.0001
Treatment 1—Treatment 4	−1.869	0.220	Inf	−8.504	<.0001
Treatment 1—Treatment 5	−0.422	0.223	Inf	−1.889	0.3229
Treatment 2—Treatment 3	−1.264	0.234	Inf	−5.407	<.0001
Treatment 2—Treatment 4	−2.194	0.239	Inf	−9.163	<.0001
Treatment 2—Treatment 5	−0.747	0.243	Inf	−3.080	0.0177
Treatment 3—Treatment 4	−0.930	0.214	Inf	−4.355	0.0001
Treatment 3—Treatment 5	0.517	0.217	Inf	2.382	0.1203
Treatment 4—Treatment 5	1.447	0.223	Inf	6.484	<.0001

Table 4 Estimated marginal means for the proportion of time bluegill spent near the control panel across different treatments

Contrast	Estimate	SE	df	z-ratio	*p*-value
Treatment 1—Treatment 2	−1.027	0.218	Inf	−4.702	<.0001
Treatment 1—Treatment 3	−0.510	0.224	Inf	−2.282	0.1507
Treatment 1—Treatment 4	0.141	0.239	Inf	0.588	0.9768
Treatment 1—Treatment 5	−0.450	0.222	Inf	−2.029	0.2519
Treatment 2—Treatment 3	0.517	0.216	Inf	2.397	0.1161
Treatment 2—Treatment 4	1.168	0.231	Inf	5.048	<.0001
Treatment 2—Treatment 5	0.577	0.214	Inf	2.696	0.0545
Treatment 3—Treatment 4	0.651	0.236	Inf	2.755	0.0464
Treatment 3—Treatment 5	0.060	0.219	Inf	0.273	0.9988
Treatment 4—Treatment 5	−0.591	0.235	Inf	−2.518	0.0865

Discussion

Bluegill are a relevant model for studying fish behavior due to their widespread distribution in North American freshwater systems (Hossain et al. 2013) and well-documented habitat requirements. In this study, we observed an interaction between fish body size and their demonstrated preferences for different panel design treatments. Specifically, we noted that small bluegill spent a large proportion of their time near experimental retaining wall panels with the highest levels of habitat complexity, whereas medium and large bluegill were less selective between different types of treatment panels but still preferred them over non-complex control panels. This preference could be attributed to the pivotal role environmental structure plays in shaping ecological interactions (Gause et al. 1936; Holt 1987; Huffaker 1958).

Armored shoreline erosion mitigation techniques have the potential to alter the physical aspects of aquatic environments in several ways, including lowering the amount of coarse woody debris introduced into the habitat (Christensen et al. 1996), decreasing the amount of aquatic macrophyte stands (Jennings et al. 2003; Radomski and Goeman 2001), and reducing the complexity of the overall littoral habitat (Schmude et al. 1998). Physical structure, nutrient inputs, and climate all play a major role in shoreline biodiversity (Strayer and Findlay 2010). The effects of riprap and retaining wall usage on shoreline habitat can also change the community compositions of fish (Brazner 1997; Bryan and Scarnecchia 1992; Jennings et al. 1999; Kornis et al. 2018; Maceina et al. 1991; Toft et al. 2007), aquatic plants (Patrick et al. 2016; Strayer et al. 2012), and benthic macroinvertebrates (Bilkovic and Mitchell 2013; Brauns et al. 2007). Additionally, these effects differ significantly depending on species-specific characteristics like habitat choice, body size, and forage items (Kornis et al. 2018). Due to the loose construction of riprap sites, which produce greater overhead cover and more physical refugia amid the unembedded rocks, Chhor et al. (2020) observed that riprap sites often provide more complex habitat than retaining wall sites (Erös et al. 2008; Garland et al. 2002; Pister 2009). Similar to terrestrial systems, there is a high correlation between species richness and aquatic habitat complexity and increasing heterogeneity (Eadie and Keast 1984; Gratwicke and Speight 2005; Roberts and

Ormond 1987). Complex habitats characterized by substrate variety and macrophyte structure can support a higher diversity of species because they facilitate a wider range of ecological niches (August 1983; Eadie and Keast 1984).

With bluegill being a mid-trophic level consumer or mesopredator, they face the challenge of balancing the conflicting demands of seeking resources and avoiding higher order predators, often simultaneously (Bolton 2016). Consequently, small alterations in habitat composition can influence its perceived value to mesopredators in habitat selection. For instance, mesopredators might opt for patches with more structure to enhance refuge value and increase survival in the presence of predation threats (Schmitt and Holbrook 1985). However, in densely structured areas, their mobility and prey detection abilities may be compromised, potentially leading to a reduction in foraging efficiency (Gotceitas and Colgan 1989). These could be some of the reasons behind the observed size-based differences in bluegill habitat preference, as interactions between habitat structure, predation risk, and foraging efficiency are significantly influenced by mobility and body size (Bartholomew 2002). Conversely, when perceived risks are lower, patches with lower complexity and less structure offer more foraging options at the cost of fewer physical refugia (Gotceitas 1990).

In this experiment, Treatment 2 (which consisted of consisted of six vertical bamboo poles) appeared to be less preferred compared to all other treatments across all three size categories (see Fig. 2). However, we observed that larger bluegill showed a preference for Treatment 5, which featured the same level of complexity but in a horizontal design, over the vertical design in Treatment 2. One potential reason for this could be that the Treatment 5 design better mimicked the natural microhabitat of bluegill. Ecosystem structure can be influenced by the vertical and horizontal orientations of physical habitat features (Glasby and Connell 2001; Knott et al. 2004). The horizontal orientation of the bamboo in Treatment 5 may recreate microhabitats with the natural features of woody debris (i.e., fallen branches or submerged logs). While vertical orientation is thought to resemble upright vegetation which helps promote macrophyte growth, a horizontal orientation may actually offer greater habitat complexity, which is a significant environmental factor affecting macroinvertebrate species (O'Connor 1991), which may attract bluegill looking for food. Smaller bluegill, however, preferred Treatment 4, the most complex panels, which may have been perceived as lower-risk due to the relative abundance of physical structure.

In the context of optimality models, organisms tend to select a habitat that maximizes their resource acquisition while minimizing the risk of predation (Werner and Gilliam 1984). Studies of how organisms use different habitat types throughout their growth often assume that each habitat possesses a singular optimal value. However, habitat patches will often feature minor variations in structural complexity that can profoundly affect the intensity of predator–prey interactions and, consequently, influence growth and survival (Yeager and Hovel 2017). In freshwater lakes, Werner and Hall (1988) demonstrated that small juvenile bluegill prefer to occupy littoral vegetated areas that offer lower predation risks and increased feeding opportunities. However, once they obtain a size refuge from predators including black bass (*Micropterus* spp.), they transition to pelagic zones associated with more abundant foraging opportunities. Similarly, juvenile Nassau grouper (*Epinephelus striatus*) in the Caribbean exhibit a shift in their preference from shallow, nearshore seagrass beds to open waters surrounding coral reefs (Dahlgren and Eggleston 2001). This suggests that younger fish are more inclined to be refuge-driven and risk-averse, while older conspecifics may be more forage-driven and risk-tolerant, opting for habitat that maximizes growth over survival (Dahlgren and Eggleston 2000).

By considering these biological and ecological factors, the observed interaction between fish body size and treatment condition suggests that bluegill respond differently to treatments where habitat complexity varied based on their individual requirements and size-specific behaviors. Specifically, incorporating natural features/textures/shapes into hard surfaces/retaining/canal walls may provide more safety for juveniles and more foraging opportunities for adults, potentially enhancing habitat quality and mitigating the negative effects of the installation of flat retaining walls. This work has already informed the next step in the development of concrete retaining walls that incorporate habitat features that represent conservation gains for freshwater life (forthcoming work). These findings emphasize the importance of incorporating animal behavior considerations into the decision-making process for habitat conservation and management (Elmer et al. 2021; Cooke et al. 2023). However, the present study had some limitations. The laboratory setting we used could not fully represent the complexity and variability of natural freshwater habitats. Additionally, the focus solely on bluegill may not render the results generalizable to other fish species and aquatic organism, or to other types of habitat alterations for which further investigation is warranted. Continued research will enhance our ability to develop effective strategies for the preservation and restoration of freshwater habitats, ultimately benefiting the diverse array of species relying on these ecosystems.

Acknowledgements This research was conducted with a Scientific Collection Permit from the Ontario Ministry of Natural Resources and Forestry, a Research Permit from Parks Canada, and with Animal Care Protocols from the Canadian Council on Animal Care (Animal Use Protocol no. 104281). We thank the staff of Queen's University Biological Station for supporting our research. We thank the anonymous reviewers for their input on our manuscript.

Funding Funding and support were provided to AFM via FishCast from the Natural Sciences and Engineering Research Council of Canada. Funding was provided to SJC via a Missions Grant from the Natural Sciences and Engineering Research Council of Canada.

Data availability Data will be made available upon request.

Declarations

Ethics approval 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).

Competing interests Dr. Steven Cooke is on the Editorial Board of this journal, but he was not involved in the peer review of this article and had no access to information regarding its peer review.

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