EFFECTS OF SURFACE ROUGHNESS ON ECOLOGICAL FUNCTION: IMPLICATIONS FOR ENGINEERED STRUCTURES WITHIN THE HUDSON RIVER SHORE ZONE

A Final Report of the Tibor T. Polgar Fellowship Program

Amy M. Villamagna

Polgar Fellow

Department of Fisheries and Wildlife Sciences
Virginia Tech
Blacksburg, VA 24061

Project Advisors:

David Strayer
Stuart Findlay
Cary Institute of Ecosystem Studies
Millbrook, NY 12545

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ABSTRACT

Shorelines are a critical and changing aspect of the Hudson River ecosystem; however, relationships between shoreline structure and ecological function of the Hudson River are not well understood. Surface complexity may affect algal accumulation, organic matter, and macroinvertebrate abundance, but no study has examined all of these components of ecological function simultaneously. In this experiment, the relationships between ecological function, surface roughness and exposure to wave energy were tested. The objective was to determine if the manipulation of surface roughness on artificial structures alters ecological function within the shore zone. Tiles with different surface roughness were deployed at four sites in the freshwater tidal Hudson River (two high-energy sites, two low-energy), and the accumulation of algae, organic matter and macroinvertebrates was measured. The macroinvertebrate community varied with surface roughness, and significantly greater macroinvertebrate density (other than zebra mussels) was found on rougher tiles. This experiment showed that surface roughness can alter ecological function, but that the effects depend at least partially on exposure to wave energy, the pre-existing food web structure, and other site-specific factors.

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INTRODUCTION

Shorelines are a critical and changing aspect of the Hudson River ecosystem. At the interface between the aquatic and terrestrial world, shorelines provide a buffer from storm-induced erosion, and serve as habitats where many aquatic and terrestrial organisms forage, find refuge and reproduce (Wei et al. 2004; Brauns et al. 2007). Shorelines may accumulate organic matter from either the terrestrial or aquatic system and there may be significant biogeochemical transformations of materials as they pass through this interface (Lambert and Sommer 2007). All of these ecological functions are likely to vary dramatically with shoreline characteristics such as slope and roughness but it is not presently know how particular functions are related to particular shorelines.

Shorelines provide people with access to water, as well as recreational and aesthetic opportunities. Waterfronts are extremely attractive areas for residential development, as can be seen with the recent increase in development in the Hudson Valley. Natural shoreline is rapidly disappearing along the Hudson River; about half of the natural Hudson River shoreline has already been replaced with engineered structures (Miller et al. 2006). Much of the modified length was altered decades ago for purposes of stabilization and as these structures have degraded there are opportunities for novel design. Based on a long history of development combined with recent improvements in water quality and the public's perception of the Hudson River, shoreline development is likely to intensify, and old engineered structures will need repair or replacement.

Relationships between shoreline structure and ecological function of the Hudson River are not well understood. Literature suggests that rougher substrates are usually linked to greater macroinvertebrate abundance and richness, as a result of a variable surface that provides microhabitats and refuges from physical stresses (Clifford et al. 1992; Way et al. 1995; Schmude et al. 1998; Strayer and Smith 2000). Experiments conducted using concrete blocks with variable surface roughness in the Mississippi River revealed more than twice as many macroinvertebrates on concrete blocks with grooves than the original smooth concrete block. The drastic difference was attributed to the microhabitat refuge from high velocity flow. Even blocks with more shallow surface irregularities were found to harbor significantly more macroinvertebrates, but taxa richness was not reported (Way et al. 1995). Texture or surface complexity can also affect algal accumulation on hard substrates with surface irregularities promoting greater accumulation of algae (Clifford et al. 1992) and organic matter (Scealy et al. 2007). Complex woody debris added to a lowland river in Australia increased macroinvertebrate richness and abundance (Scealy et al. 2007), with more organic material trapped in complex woody debris in riffle sites (i.e. higher energy) than in pools. The relationships between substrate complexity, organic matter, and macroinvertebrate richness and abundance suggest that potential modifications in shoreline construction or materials could increase ecological function within the shore zone.

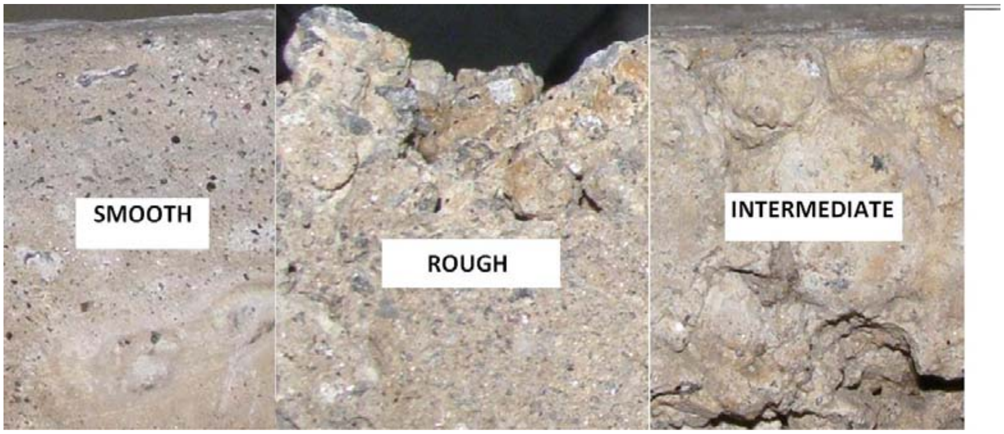
Algae, organic matter and macroinvertebrates provide the ecological foundation (i.e. food resources) for higher trophic levels, including fish and bird populations. In this study, the hypothesis that rough tiles retain greater organic matter, algae and more macroinvertebrates than smooth tiles was tested. The specific objective was to investigate the effects of surface roughness and exposure to wave intensity on the accumulation of organic matter, growth of chlorophyll *a* and the colonization of macroinvertebrates within the shore zone of the tidal freshwater Hudson River.

METHODS

During the first week of May 2008, 120 experimental concrete tiles were created using 15.24 in^2 square, commercially available plastic and hand-made wood molds. Forty tiles of each surface roughness were crafted to be smooth, intermediately rough and rough (Figure 1). Surface roughness was manipulated by varying the amount of water added to the concrete mix. Each tile was about 1.5 inches thick. The smooth tiles were smoothed to prevent cracks and crevices. Rough tiles were manipulated to include crevices and peaks, while intermediate tiles were smoothed, but crevices were enhanced.

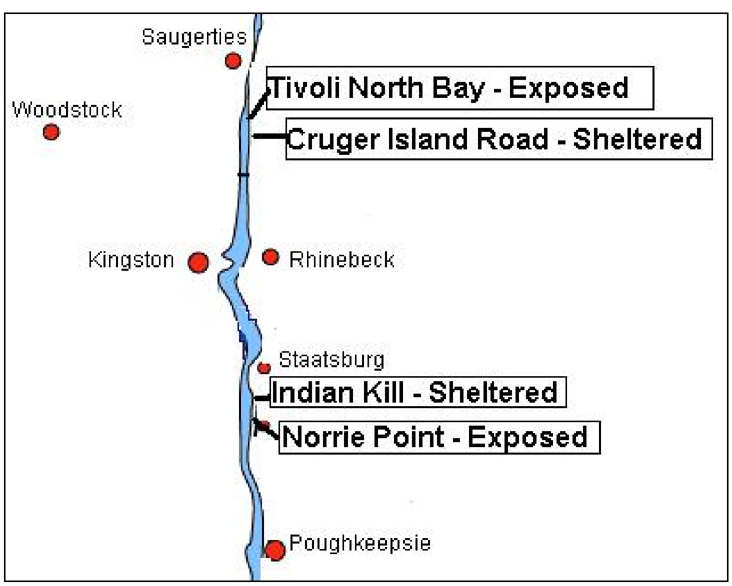
Four sites (Figure 2) were selected within the Mid-Hudson region: two high-energy sites (exposed) and two low-energy sites (sheltered). Rough tiles in high energy environments were expected to act as a refuge from the stressful outer environment, thus having a stronger effect on organic matter accumulation, algal growth and macroinvertebrate abundance than smoother tiles. Tiles were placed vertically to mimic the walls of artificial structures and to avoid deposition of detritus and sediment from the water column (Vollenweider 1969).

Figure 1: Cross-section of tiles showing surface roughness.



Sheltered sites were established in tidal creeks less than 5 m wide with densely vegetated stream banks adjacent to the Hudson River. Both sheltered sites experienced minimal human disturbance during the study. Exposed sites shared a rocky bottom substrate. Submerged vegetation increased in sheltered sites during the study. Water chestnut became prevalent at the Norrie Point exposed sites, but was not as much of a factor at the Tivoli North Bay exposed site.

Figure 2: Site Locations



Tiles were placed within the sheltered sites on May 13 and 14, 2008, and were grouped in ten clusters of three, each consisting of a smooth, intermediate and rough tile. The soft stream bottom within sheltered areas allowed us to anchor tiles directly to the bottom using heavy-duty wire braces (Figure 3, left). Tiles were placed approximately 0.5 m below the low water mark.

Figure 3: Tile stabilization structures. Wire anchors for sheltered sites (left) and concrete composites for exposed sites (right).

The exposed tile composites (Figure 3, right) were placed into the river at ten locations within the site reach on May 20 and 21, 2008. A single tile of each substrate type was glued to a concrete patio block 18"x 6"x 2.5" using a hybrid waterproof adhesive and sealant. The composites were required to maintain vertical alignment in the high energy sites where rocky substrate did not allow for wire braces.

Tiles were removed after ten weeks during the week of July 21-28, 2008. The increase in submerged vegetation and sediment made it difficult to find tiles. Tiles were placed in individually sealed bags and transported to the lab at the Cary Institute of Ecosystem Studies. In the lab, tiles were scrubbed into a bucket of water to create a 500 ml slurry solution. A toothbrush, hairbrush and barbeque brush were used to scrub the tiles. Tiles were scrubbed within 12 hours of removal from the river. A 40 ml subsample for organic matter analysis and a 30 ml subsample for chlorophyll *a* analysis were collected from the slurry. The remaining 430 ml solution was filtered through a 0.5 mm mesh for macroinvertebrate identification and counting.

Organic matter analysis

Organic matter samples were placed in small tin collection pans and placed in the drying oven (18-24hours), re-weighed, and combusted at 450 degrees C for 4 hours. When cooled the tins were reweighed to obtain the ash-free dry mass (organic matter).

Chlorophyll a analysis

The chlorophyll *a* samples were centrifuged to collect material in a pellet and water was then gently decanted. The tube with remaining pellet was stored in a freezer until the day before extraction when tubes were frozen to -20 degrees C. Then 20 ml of methanol was added to each sample tube and heated in a water bath at 65 degrees C for 5 minutes. Samples were removed and stored in the dark at room temperature for 24 hrs. This methodology was adapted from (Sartory and Grobbelaar 1984) to facilitate the chlorophyll *a* extraction from benthic samples.

The following day, samples were diluted (1 ml extract + 5 ml MeOH) into fluorometer tubes. Wavelength absorption was measured at 665 nm before acidification (0.1 ml N HCl), and 750 nm after acidification to account for chlorophyll *a* and pheophytin (Steinman et al. 2006). If the fluorescence response exceeded 800 units before acidification the samples were diluted again by combining 1 ml of the prepared solution to another 5 ml of MeOH. The final chlorophyll *a* content of samples was calculated using the equations provided in Parsons et al. (1984).

Macroinvertebrates

Macroinvertebrates were filtered from the slurry and stored in 70% ethanol until they could be counted and identified under a dissecting scope. All organisms found in each sample were counted. Where zebra mussels exceeded 20 individuals in the first subsection of the collection plate, all non-zebra mussel taxa were counted, then subsampled to count zebra mussels. Organisms were identified to class, and where possible order. A list of all taxa observed and their functional feeding groups is provided in Table 1. Functional feeding groups are broad categories based on body structure and behavioral mechanisms used for feeding (Voshell 2002).

Table 1: Taxa observed in Hudson River artificial substrate study May-July 2008.

Class	Order	Function Group
Gastropoda	-	Scrapers
Bivalvia	Veneroida (predominantly Dreissenidae)	Collector-Filterer
Hirudinea	-	Predator
Oligochaeta	-	Collector-Gatherer
Turbellaria	-	Predators, Collector-Gatherer
Insecta	Ephemeroptera	Collector-Gatherer, Scraper
Insecta	Plecoptera	Shredder, Predator
Insecta	Coleoptera (predominantly Elmidae)	All (scraper, collector-gatherer)
Insecta	Diptera	Shredders, Collectors
Insecta	Trichoptera	All
Insecta	Odonata	Collector-Gatherer
Arachnida	Hydracarina	Predator
Crustacea	Isopoda	Mostly Collector-Gatherer
Crustacea	Amphipoda	Multiple functional feeding groups
Coelenterata	-	Predator
Crustacea	Ostracoda	Collector-Filterer
Crustacea	Cladocera	Collector-Filterer

Statistical analysis

The null hypotheses for organic matter and chlorophyll *a* were tested using a mixed model analysis of variance where site was a random effect and exposure and surface roughness as fixed (treatment) effects. The chlorophyll *a* and organic matter data was log-transformed to adjust for a non-normal distribution. A similar approach was used to test the null hypothesis for macroinvertebrate abundance, and non-metric multidimensional scaling (NMDS) was used to analyze the macroinvertebrate community structure among substrate types in exposed and sheltered sites. NMDS calculates a Sorenson distance matrix and creates an ordination that illustrates this matrix in a low-dimensional space (2 or 3 dimensions) (Zuur and Ieno 2007). NMDS is based on the ranking or order of distances between subjects.

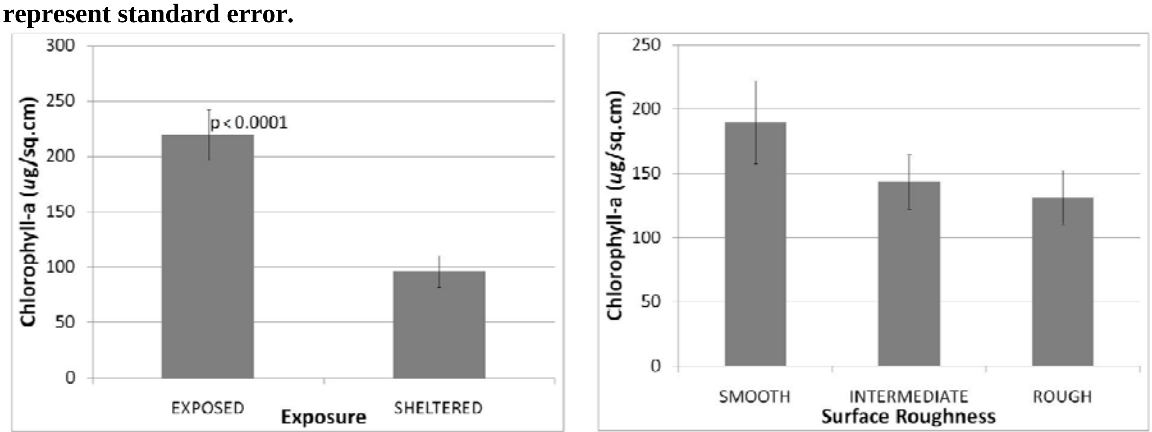
The relationship between organic matter and macroinvertebrate abundance, and chlorophyll *a* concentrations and macroinvertebrate abundance was tested statistically by linear regression. Only tiles for which both sets of data existed (i.e. organic matter or chlorophyll *a* and macroinvertebrate abundance) were included in this regression analysis.

RESULTS

<u>Chlorophyll *a* and Organic Matter</u>

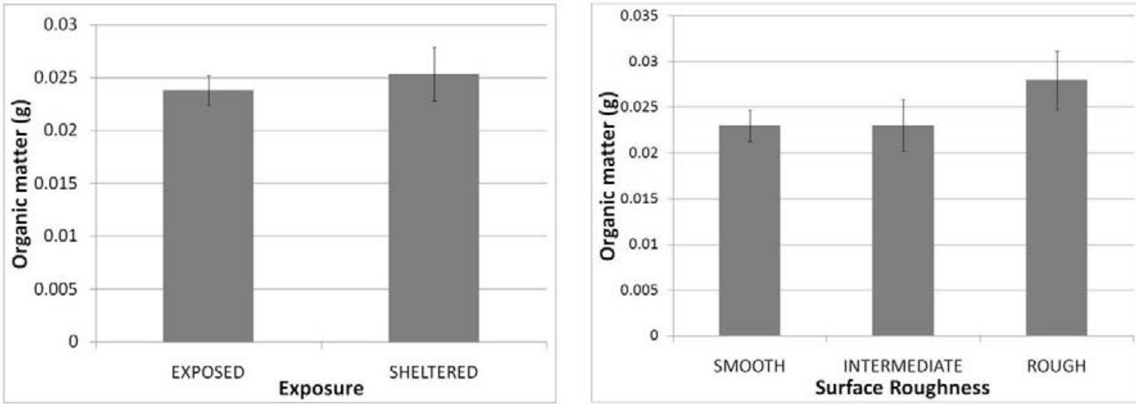
Surface roughness was not a significant determinant of chlorophyll *a* accumulation; exposure to wave energy was the only statistically significant factor ($p < 0.0001$) explaining the observed results (Figure 4).

Figure 4: The effects of exposure (left) and surface roughness (right) on chlorophyll *a*. Exposure was a significant factor ($p<0.001$), however surface roughness was not significant ($p = 0.7371$). Bars represent standard error.



OM accumulation did not differ significantly between exposure or among roughness ($p = 0.47$ and $p = 0.81$, respectively); therefore, the null hypothesis could not be rejected (Figure 5).

Figure 5: The effects of exposure (left) and surface roughness (right) on organic matter accumulation. There was no significant difference in organic matter accumulation between exposed and sheltered sites (p = 0.47) or among roughness tiles (p = 0.81). Bars represent standard error.

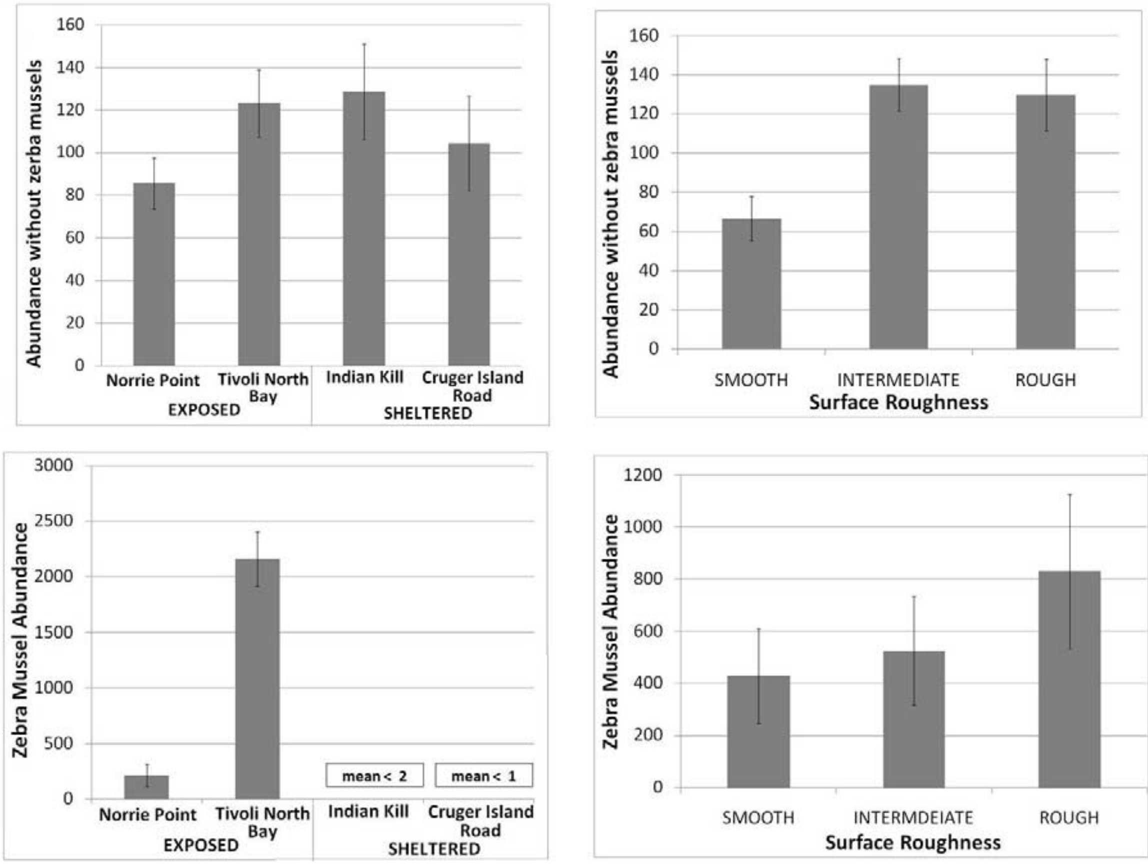


<u>Macroinvertebrates</u>

Abundance

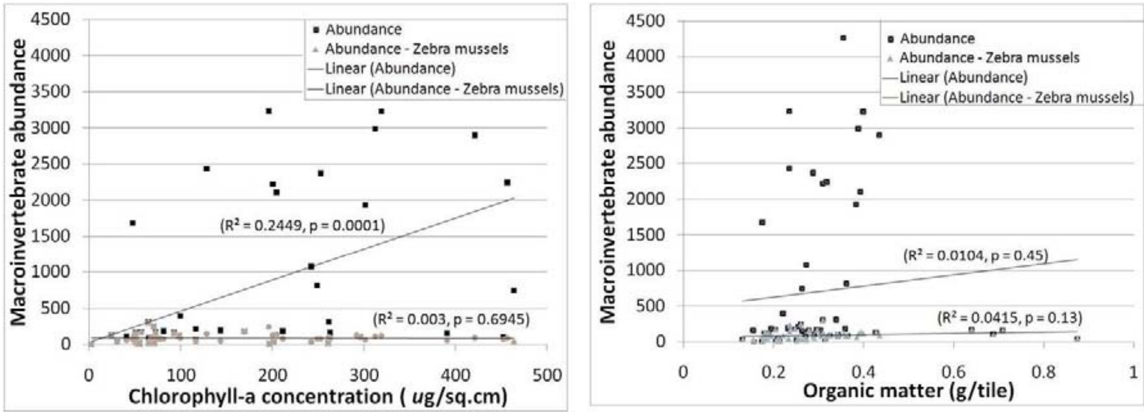
Exposure was a statistically significant factor ($p < 0.0001$) explaining the variability in density observed in this experiment. Tiles in exposed sites supported more macroinvertebrates than in sheltered sites. This disproved the original expectation of more macroinvertebrates within sheltered sites where wave energy was less intense. Neither surface roughness ($p = 0.14$) or the interaction of both factors ($p = 0.22$) was a significant factor explaining macroinvertebrate abundance. The effect of exposure was attributed to the dominant presence of zebra mussels within exposed sites, particularly the Tivoli North Bay site (Figure 6; bottom left). When tile density was recalculated to exclude zebra mussels, exposure was no longer a significant factor ($p = 0.48$), but surface roughness became a significant factor ($p = 0.0028$) explaining observed variability (Figure 6, top). In both scenarios, intermediate and rough tiles supported more macroinvertebrates overall, and more zebra mussels, than smooth tiles.

Figure 6: The effects of exposure (top left) and surface roughness (top right) on macroinvertebrate abundance without zebra mussels and the effects of exposure (bottom left) and surface roughness (bottom right) on zebra mussel abundance Bars represent standard error. Exposure was a significant factor (p < 0.0001) in the observed abundance of macroinvertebrates (minus zebra mussels), but surface roughness was not (p = 0.14). Likewise, exposure was a significant factor explaining observed zebra mussel abundance (p < 0.001), while surface roughness was not (p = 0.1675).



There was not a strong relationship between organic matter accumulation and macroinvertebrate density on individual tiles; however, there was a significant (p<0.0001) positive relationship between chlorophyll *a* concentration and total macroinvertebrate abundance (Figure 7).

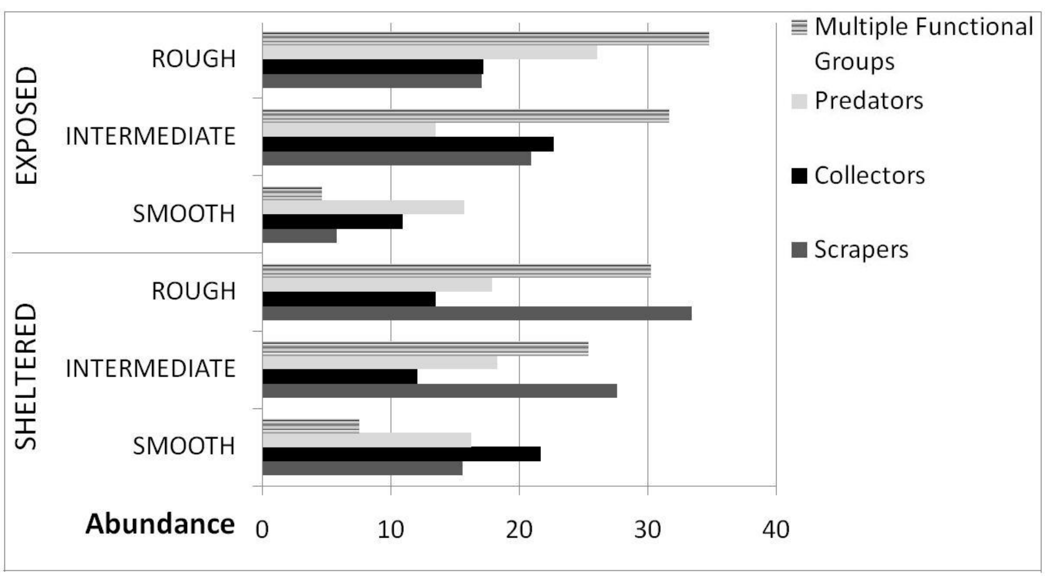
Figure 7: The relationship between macroinvertebrate density and organic matter and chlorophyll *a* accumulation.



Functional Feeding Groups

Figure 8 illustrates functional feeding group (FFG) density on all tiles at exposed and sheltered sites. Each functional group includes organisms that are considered members of only one function group. Those that play several functional roles are aggregated in the “Multiple Functional Groups” class. The predator group included Turbellaria, Hirudinea, and Hydracarina; the scraper group included Gastropoda and

Figure 8: The effects of exposure and surface roughness on different functional feeding groups. Predators = Turbellaria, Hirudinea, and Hydracarina; Collectors = Oligochaeta, Bivalvia, and Diptera; Scrapers = Gastropoda and Coleoptera larvae; Multiple Functional Groups = Isopoda, Amphipoda, and Trichoptera. Zebra mussels were excluded from collectors group (denoted with *) in this graph to facilitate comparisons.



Coleoptera larvae; the collector group included Oligochaeta, Bivalvia, and Diptera; and the “multiple functional groups” included Isopoda, Amphipoda, and Trichoptera (Voshell 2002). Zebra mussels are excluded from the exposed sites in Figure 8 to enhance the view for comparison. The density of scrapers found on tiles in sheltered areas was less than found in the exposed sites, but the density of predators was higher. Macroinvertebrate community structure was expressed by NMS ordinations illustrated in Figures 9-11. The distance between points (individual tiles) in an ordination is inversely proportional to their taxonomic similarity. Table 2 reports the dimensionality of the ordination results and the stress level. Stress measures the fit of the ordination created. According to Clarke’s rules of thumb, stress value less than 10 is considered good with a small chance of misinterpretation, between ten and twenty is considered fair, but stress greater than 15 is considered unreliable (Clarke 1993).

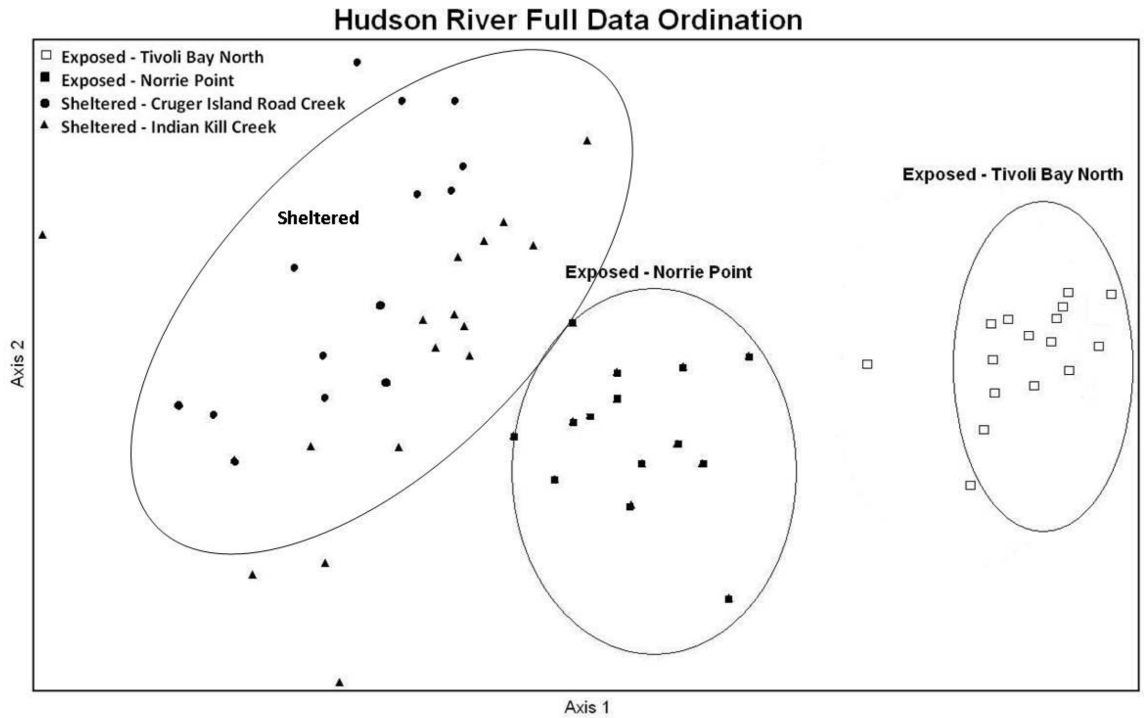
Table 2: Dimensionality and stress results from the NMS ordination.

Site	Number of axes	Stress
Full Hudson River Study Data	2	11 (Fairly good ordination)
Indian Kill (S)	2	14 (Fair ordination)
Cruger Island Road Tidal Creek (S)	2	9 (Good ordination)
Tivoli North Bay (E)	2	No ordination possible
Tivoli North Bay (E), no zebra mussels	2	11 (Fairly good ordination)
Norrie Point Environmental Center (E)	2	7 (Good ordination)

The full data set ordination indicated a fairly clear grouping by site. The ordination suggested that the macroinvertebrate communities within exposed sites had stronger intra-site similarity than the sheltered sites (Figure 9). There is greater distance between the two exposed sites than there is between the sheltered sites, suggesting greater similarity between sheltered sites than between exposed sites.

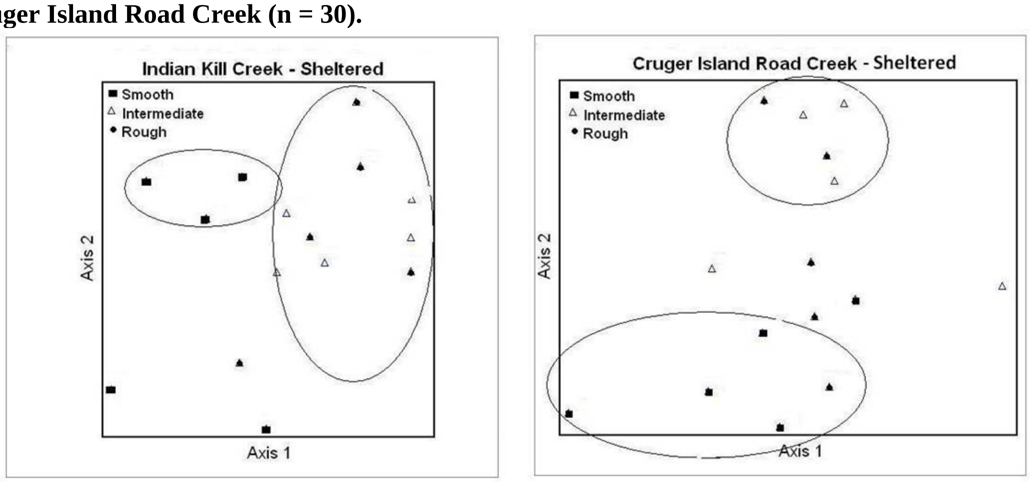
Site-specific ordinations were run to facilitate the visual analysis of trends with respect to surface roughness. The Indian Kill sheltered site shows a grouping of intermediate and rough tiles being more similar to each other than with the community of smooth tiles (Figure 10). Community structure among smooth tile replicates varied based on this graphical depiction of Bray-Curtis distance, with only three of five tiles being

Figure 9: Macroinvertebrate community structure at all sites. (n = 120).



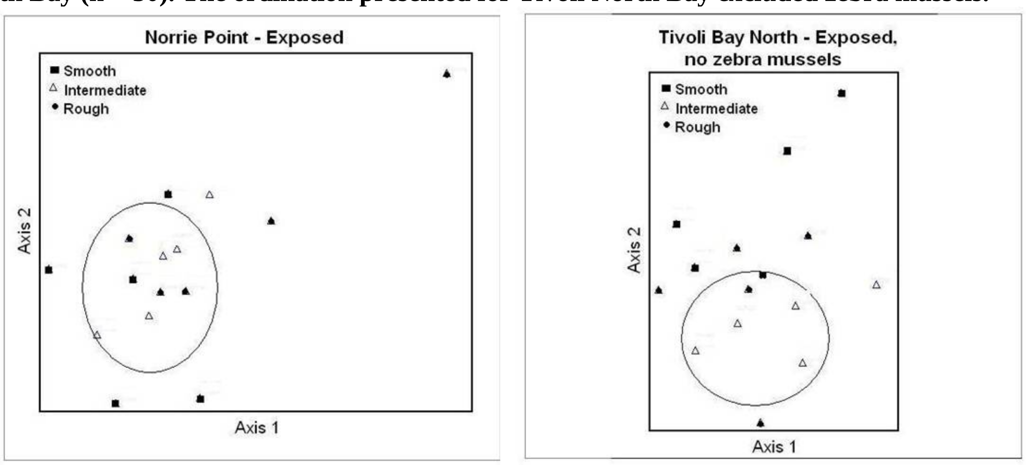
placed adjacent to each other. The Cruger Island Road Tidal Creek site demonstrated stronger clustering between rough and intermediate tile communities than the other sites (Figure 10). The variability among smooth tile replicates was also less than other tiles, with 4 of 5 tiles placed adjacent to each other.

Figure 10: Macroinvertebrate community structure at sheltered sites: Indian Kill Creek (n = 30) and Cruger Island Road Creek (n = 30).



Community structure on smooth tiles was especially variable at the Norrie Point exposed site as is illustrated with the scattered depiction in Figure 11. Intermediate and rough tile communities appear more similar to each other than with smooth tile communities. A relatively tight clustering of rough and intermediate tiles (8 of 10) is evident from this ordination. A useful ordination was not found for the exposed site at Tivoli North. This is either because the structure of the community was too weak or a single variable has too much weight. The latter is most probable due to the prevalence of zebra mussels at this site (mean density = 2160 mussels). When the ordination was rerun on community data excluding zebra mussels a fairly good ordination was found. In general, clustering is not as strong in this ordination. Only the intermediate tiles are somewhat closely related to each other. Overall, there is a relatively weak pattern of intra-site similarity among tile types.

Figure 11: Macroinvertebrate community structure at exposed sites: Norrie Point (n = 30) and Tivoli North Bay (n = 30). The ordination presented for Tivoli North Bay excluded zebra mussels.



DISCUSSION

Overall, surface roughness did not strongly affect chlorophyll *a*, organic matter, or macroinvertebrate abundance. These results differed from other results cited in the literature (Way et al. 1995) and from expectations at the onset of this experiment. A greater accumulation of both organic matter and chlorophyll *a* in sheltered areas was expected where water movement was slower and calmer than at the exposed sites.

Instead, there was greater chlorophyll *a* growth in exposed sites and on smooth tiles. While organic matter accumulation was somewhat greater within sheltered sites and on rough tiles, the differences were not statistically significant. Organic matter accumulation was expected to follow a similar pattern as chlorophyll *a*, but this was not observed in this experiment. Moreover, prior studies suggest zebra mussels increase macroinvertebrate density through the provision of increased substrate for colonization (Hovarth et al. 1999), but there were not significantly more macroinvertebrates on tiles with zebra mussels than tiles without zebra mussels. In fact, the highest macroinvertebrate tile density (excluding zebra mussels) was found at Indian Kill Creek sheltered site where mean zebra mussel density was less than 2 individuals (Figure 6).

Table 3: A summary of experiment results. Statistical significance ($p < 0.05$) is denoted by (*).

Variables	Exposure	Roughness
Organic matter	Exposed < Sheltered	$S = I \leq R$
Chlorophyll *a*	Exposed > Sheltered*	$S > I \geq R$
Macroinvertebrate abundance	Exposed > Sheltered	$S = I = R$
Macroinvertebrate abundance, without zebra mussels	Exposed = Sheltered	$S < I > R$*
Macroinvertebrate community structure	Exposed: strong within-site similarity. Sheltered: weak within-site similarity	Weak clusters
Chlorophyll *a* and Macroinvertebrate abundance	Highly significant, but fairly weak correlation (0.2449, $p = 0.0001$)	
Organic matter and Macroinvertebrate abundance	No significant correlation	

Surface roughness did appear to play a role in determining the structure of macroinvertebrate communities. A consistent similarity was found between the macroinvertebrate community structure of rough and intermediate tiles from our within-site analysis. Although these tiles were created to be different, intermediate tiles were more similar to rough tiles than to smooth tiles. The similarity detected among intermediate and rough tiles to microhabitat heterogeneity was attributed to the provision of refuge from predators, and the actual design of the tiles.

Implications for shore zone development

Surface roughness of artificial structures may influence ecological function within the shore zone, but the effect seemed to vary with exposure and with location. Despite the conflicting results of the organic matter and chlorophyll *a* analyses, macroinvertebrate abundance was higher on intermediate and rough tiles than on smoother tiles. An overall positive correlation between chlorophyll *a* and macroinvertebrate abundance was found, but it is difficult to know what is determining the observed chlorophyll *a* results. For instance, low chlorophyll *a* could represent low photosynthetic production or high grazing pressure. Experiments that specifically test production and predation would strengthen the understanding of the relationship between chlorophyll *a* and surface roughness. Similarly, the direct cause of observed macroinvertebrate abundance could be higher chlorophyll *a* production or greater refuge from predators. Again, experiments that isolate these processes are needed to better explain our results.

Even though the results of this study support the idea that macroinvertebrate abundance increases with increased surface roughness, the question remains whether a numerical increase in macroinvertebrates is equivalent to enhancing ecological function. There were more zebra mussels at exposed sites. In these cases, an increase in macroinvertebrates may not be considered ecological enhancement. Perhaps a better measure would be taxonomic richness or diversity. The functional feeding group approach may also provide a helpful snapshot of the community-level response to surface roughness. In both exposed and sheltered areas, the abundance of predators and multiple functional group taxa increased with increasing surface roughness. This could suggest rougher surfaces promote a more diversified community of prey resources that is attractive to predators. However, a study that identifies macroinvertebrates to genus or species could avoid the ambiguity (i.e. the “multiple feeding groups” class) associated with the functional feeding group analysis presented here.

This experiment attempted to minimize variability within exposed and sheltered sites, but differences between sites of a given exposure were detected for chlorophyll *a* and the macroinvertebrate community. In the future it would be helpful to quantify more site characteristics (e.g. wave energy, water clarity, benthic substrate, predation pressure, etc) in efforts to minimize variability among treatment sites and increase consistency within the results.

The results of this experiment suggest that surface roughness of artificial structures has the potential to affect ecological function, but that the magnitude of the effects depends on exposure to wave energy, the presence of ecosystem-altering species (i.e. zebra mussels), and perhaps other site-specific characteristics. Nevertheless, there was not a negative relationship between surface roughness and chlorophyll *a*, organic matter, or macroinvertebrate abundance. Therefore, where possible, short-term experiments should be conducted at specific sites targeted for waterfront development to determine the potential ecological enhancements associated with surface roughness. Ecological function can be compared to the pre-existing ecological function to determine which roughness is most appropriate to maintain or enhance ecological function. When experimentation is not possible, this study supports the use of rougher substrates in waterfront development projects, providing the cost difference is small.

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