Coupling Ecological Productivity with Anthropogenic Waste Streams to Regenerate Coastlines

Today's planning, design and construction professionals are confronted with the formidable challenge of creating conditions that enable humans to thrive without compromising the ecological function of the environment.

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The world's coastlines are experiencing unprecedented levels of stress from global economic growth in the form of urban development, land reclamation, aquaculture and the concurrent pollution these alterations bring. Over half the world population lives on or near coastlines, putting immense pressure on these fragile environments and leading to a precipitous decline in the world's wetland, seagrass and coral reef ecosystems.[1,2] With rapid population growth projected to continue in coastal urban areas in the coming decades, these trends forecast a catastrophic scenario for the global diversity associated with nearshore environments.

Mangroves, which are tropical and subtropical intertidal forests, are absolutely critical to the transitional nature of coastlines where they occur. These ecosystems provide habitat for marine and terrestrial species, secure shorelines with elaborate root structures and filter runoff from upland ecosystems and urban sources.[1,3,4] In lieu of these ecological services, over one third of the world's original mangrove forest cover has been lost, with a rate of disappearance that exceeds the tropical rainforests.[5] These losses represent a major reduction in available nursery habitat for a wide variety of species, many of which humans depend on for food.

In South Florida, the loss of mangrove forests is mostly due to coastal urban development, where rigid vertical seawalls have replaced thriving tidal habitats. Large-scale civil landscape works, meant to improve human habitat, have degraded indigenous vegetation and reduced these systems' capacity to filter runoff from urban and agricultural sources. Simultaneous to this, coastal communities have become more vulnerable to threats from the environment, as natural protective buffers have been replaced with barriers susceptible to long-term erosion and catastrophic failure.[6] These engineered systems lack the adaptability of natural shorelines, which means they are far more likely to succumb to the threats of sea level rise and increasingly turbulent weather patterns. Already, hundreds of thousands of people residing within coastal communities fall victim to catastrophes each year (tropical storms, tsunamis and environmental degradation). The economic damage from these events extends into the billions of dollars annually, leading some to question the viability of continuing to build-out coastlines with conventional structures in these hazard prone and ecologically fragile areas.

Engineered shoreline structures, such as seawalls and bulkheads, have been previously accepted as a method to armor coastlines against the natural morphological processes that shape coastal zones, while natural protective buffers, such as mangroves, have only recently gained attention for providing these services. Furthermore, natural buffer structures have many infrastructural benefits over their constructed counterparts. For example, while constructed landscapes and infrastructure are costly to install and maintain, natural systems, such as mangroves, are self-sufficient and capable of absorbing pollutants delivered in runoff. These forests utilize nutrient-loaded runoff for growth and reproduction, a positive byproduct of an otherwise negative contribution to the environment.

Currently, there are no studies on the large-scale urban integration of mangrove forests with regards to ecosystem services, as well as no knowledge on coupling these trees with engineered systems as proposed in this project. In addition, there is a critical need for research methods and models that span across scales and disciplines and couple the large-scale analysis of ecological services and human well-being with the mechanistic functions of human-altered environments.[7] This research project proposes a design intervention that relies on multiple data sets to scale and integrate living systems within engineered structures to create reinforced living shorelines. These integrated natural systems are further enhanced through a strategic alignment of anthropogenic waste streams to amplify the growth and diversification of a hybrid (urban-natural) ecosystem. The research takes a site located on the west coast of Florida to design the intervention based on measured pollutant loads and uses local data on nutrient loading in Lemon Bay to determine an appropriate scale of system deployment, in the form of a coupled mangrove and oyster technology (Bio-remediative Mangrove Oyster Project, or "BioMOP"). The nutrient contributions of the community are used to scale the system, which in turn influences the design by determining characteristic length to width ratio for biological extraction of pollutants without compromising the economic appeal of local resorts and residences.

BACKGROUND

As they are currently (and historically) built, bulkheads and seawalls prohibit colonization by natural mangrove vegetation. [Figure 1] Whereas mangrove shorelines are permeable and reduce wave energy gradually with a "feathered" shoreline (Figure 1, right), rigid vertical walls amplify wave action and erosion, and in many cases undermine the structural integrity of these "permanent" installations.[6] Large-scale construction dwarfs mangrove seedlings in scale, and scour and erosion from conventional civil coastline structures prevents intertidal zones from forming by normal sedimentation, thereby preventing the

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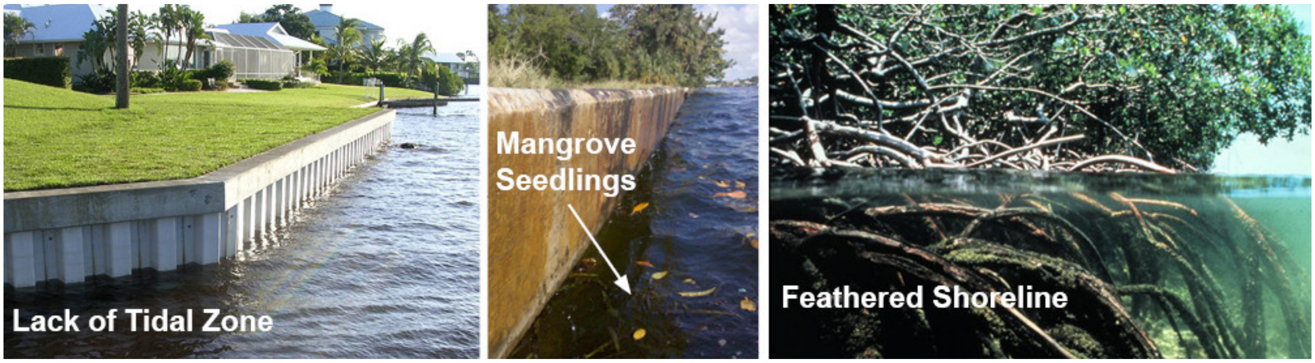
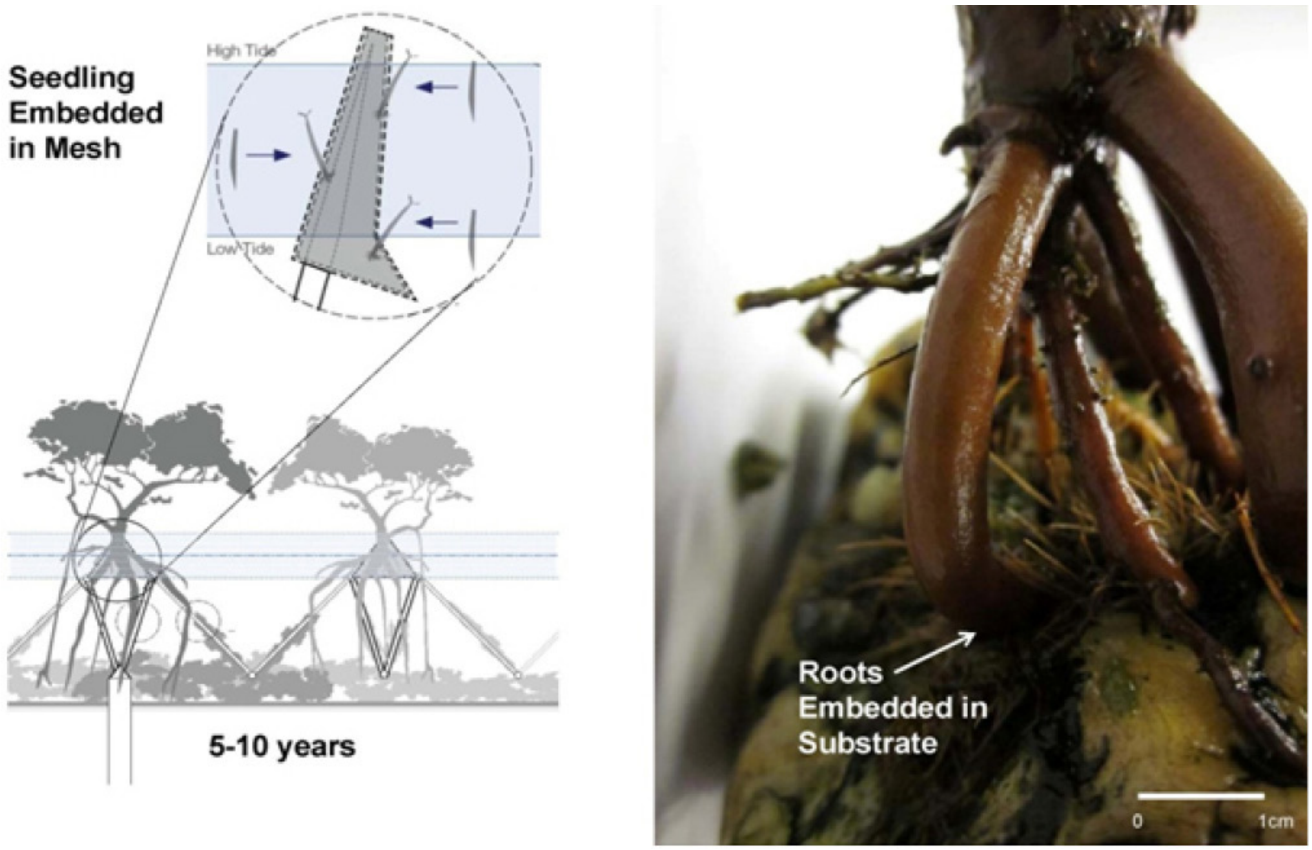


Figure 1: (left) Typical bulkhead shoreline in South Florida; (middle) rigid vertical walls impede mangrove seedling colonization; (right) natural South Florida red mangrove tidal transition with characteristic aerial prop roots [11]

development of replantable substrates.[8,9] Deepwater habitats form near these rigid urban surfaces, which reduces natural protective features, such as mangrove and seagrasses, and further eliminates the possibility of natural recolonization by mangroves, as formation of intertidal zones is precluded.[8,9,10] Mangrove seedlings require tidal landings to become established, and these environments present formidable conditions for waterborne mangrove seedlings.

Several methods are currently used to restore mangrove forests, though these methods are mainly focused on limited tree restoration in existing tidal zones rather than integration within the types of urban environments described above. Seedlings are often planted directly on tidal flats, or sometimes marsh plants are utilized to stabilize soils, trap mangrove propagules, and facilitate mangrove seedling growth by changing micro-environmental conditions.[12] These strategies capitalize on the propagation of mangroves, as seedlings have exceptional colonization ability and can even take root and grow in atypical porous substrates, such as rocky shores, if environmental conditions are favorable. Reef Ball Mangrove Solutions Division promotes a planter substrate that is placed directly in the soil with reinforcing vertical bars where necessary, but this technology has limited depth applications and is mostly designed for wave protection in mudflats.[13] In the Lower Florida Keys, bags of oyster shell arranged like a shallow wall have been used as a "mangrove planter" to provide wavebreak support for mangroves. These types of systems are used occasionally with other communities [bare bottom benthic, seagrass, etc] to produce what is termed a "living shoreline" system. In some sites, planting mangroves within PVC tubes partially filled with sediment has been employed along high energy shorelines, some places known as the "Riley Encasement Method."[14] In general, these methods lack the ability to deal with depths associated with urban edges, and do not address wave energy near seawalls and bulkheads. Ultimately, a suitable tidal substrate must be present to promote the establishment and growth of mangroves. Lewis (2000) presents a case for re-grading the landscape where tidal zones can be reestablished, though this method can be costly and difficult in some sites, particularly with regards to large-scale urban regions.[15] In addition, the depth of water near urban structures may require too significant amount of material for infill purposes.

In contrast to the rigid vertical walls of conventional shoreline structures, mangrove forests are conducive to their own propagation. Dense root structures form matrix-like conditions for seedlings to become entrapped. Once caught in a tidal substrate, seedlings can develop and grow as if planted in a



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more typical soil substrate. In addition, tidal mud flats and oyster colonies form suitable substrates for seedlings. Both of these ecosystems are intertidal and therefore maintaining or restoring proper hydrological regime (tidal cycle) is critical to success of a replanting effort.[15,16]

Within this study, an alternative technology for establishing mangrove-like vegetation within hostile environments (Van de Riet et al., 2012) was utilized to provide a tidal "scaffold" for seedlings to colonize and grow.[17] The matrix characteristic of the system creates mangrove-like conditions to facilitate the development of seedlings. [Figure 2] This system provides a tidal substrate for mangroves and oysters to colonize near compromised shorelines and can be tailored for specific purposes – wave protection, erosion control, remediation of runoff, or all of the above. In the case of storm wave protection, the system utilizes anchors in the seabed to reinforce newly colonized mangrove and oyster colonies, thereby amplifying the wave absorption capacity with a prosthetic strengthening device. The density of structure can be modified to control erosion in areas subject to wave action from storms or boat traffic, with long-term performance improved by the infill of mangrove and oysters over time. In the case of the present study in Lemon Bay, FL, the primary function was to remediate nitrogen loading in the bay, with wave erosion from boat traffic serving as a secondary role. This system was modified according to the site-specific requirements and allowed mangrove vegetation to be "landscaped" according to patterns that promote growth and maintain zones of human inhabitance and recreation. In order to demonstrate the application of the technology, determining the scale according to site-specific nutrient loads and spatial constraints of a recreational shoreline is critical to measure

Figure 2: Patented Technology (Van de Riet, et al., 2013) for Securing Mangrove Trees and Oysters on an Artificial Tidal Reinforcement Structure

the success of the system, in order to determine its viability as a design integration prior to its being built.

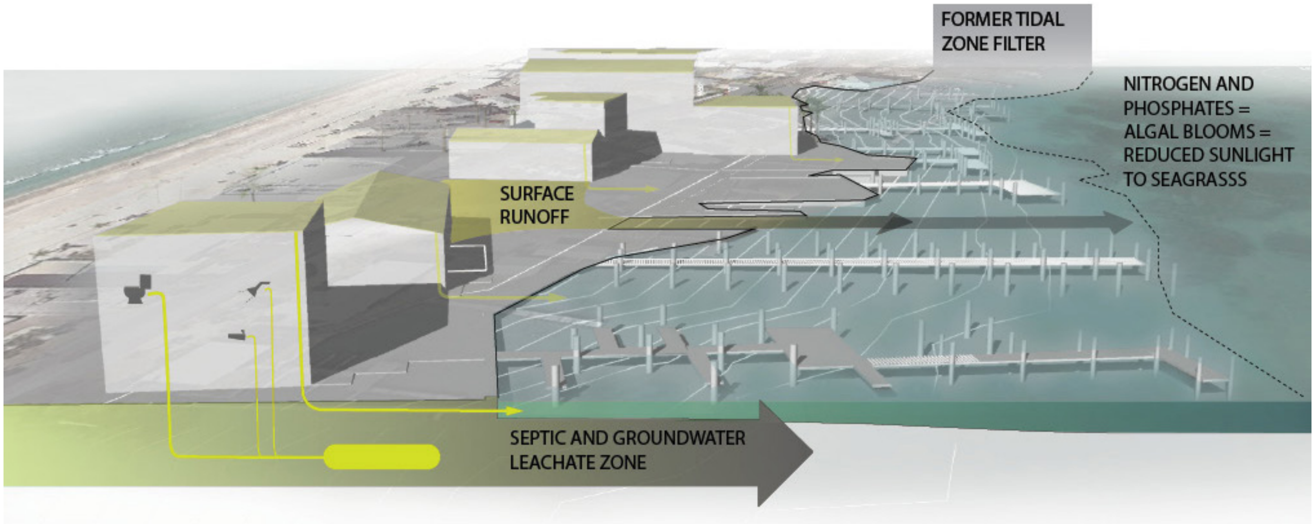
LEMON BAY REGIONAL STUDY

Water quality monitoring of the Lemon Bay area was undertaken in recent decades by Tomasko et al., (2001, 2005).[18,19] The results of this research indicated a correlation between urbanization and nutrient loads in the bay. As Lemon Bay become more urban, nitrogen levels associated with human development increasingly reached the bay. From pre-development (1850) to recent conditions (1995), the nitrogen loads in Lemon Bay increased by 59%.[18] By 2010, loads were predicted to increase by an additional 45%-58%. Data on the actual current loads as compared to the projections was not published as of this study, and therefore, the projected 45%-58% increase in loading was used in the formation of parameters.

In the 1980's, the Sarasota, FL region to the north of Lemon Bay underwent a number of large-scale wastewater treatment improvements to limit the number of residential and commercial septic tanks located near the water. This significantly reduced point loads in the form of waste leach into the water table, and shifted the focus to more general runoff as the primary pollutant.[19] In the Lemon Bay area, upgrades from septic tanks have not been widely adopted as in the Sarasota region, and as a result, multiple sources are to blame for the pollution. Many distributed septic point loads contribute leachate to the bay causing a number of environmental problems. Increased chlorophyll in the water fed by available nitrogen reduces the depth of light penetration, thereby reducing available solar access for seagrass communities. The available habitat for seagrass was projected to decrease by 24% with an increase in annual nitrogen loads of 29%, as a result of reduced light penetration.[18] Although the origin of water pollution remains somewhat variable from site to site, the common point of entry remains at the shoreline, where contaminated groundwater and surface runoff migrate into the marine environment. In both cases (surface and subsurface contributions), the ideal treatment location is at the shoreline. [Figure 3]

Ecosystem services have long been studied and gained considerable attention in the wake of major environmental catastrophes. For example, emergent and near emergent vegetation, as well as coral reefs and other landscape features, have been attributed critical roles in wave energy absorption and erosion control, particularly following the Indian Ocean Tsunami in 2004. Along with this shoreline protective benefit, these ecosystems play a biochemical role in the environment that contributes to diversity and balance, as well as water quality control. The EPA reported that wetlands perform to some degree, the biochemical transformations of wastewater treatment common to anthropogenic methods, indicating a potential use for these ecosystems in anthropogenic waste streams.[20] These ecological processes engage a number of pollutants as nutrients, in many cases using the "waste" for growth and development.

The opportunity to utilize natural systems depends on the ability of the species involved to absorb and sequester pollutants, without compromising the integrity of the particular plant or animal. In the case of mangroves, these trees utilize nutrients for biological growth and reproduction, a potential beneficial byproduct of waste disposal. Rates of nitrogen removal can vary by species and in relation to geographical and climatic factors. Rivera-Monroy et al.,



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(1999) found total "losses" of nitrogen in mangroves through denitrification, accumulation in soil and plant uptake to be 2.24 kg/ha per day.[21] Furthermore, mangrove ecosystems have been shown to have a high capacity to sequester heavy metals, in addition to the surplus nutrients, thereby preventing these toxic hazards from entering the food web.[4]

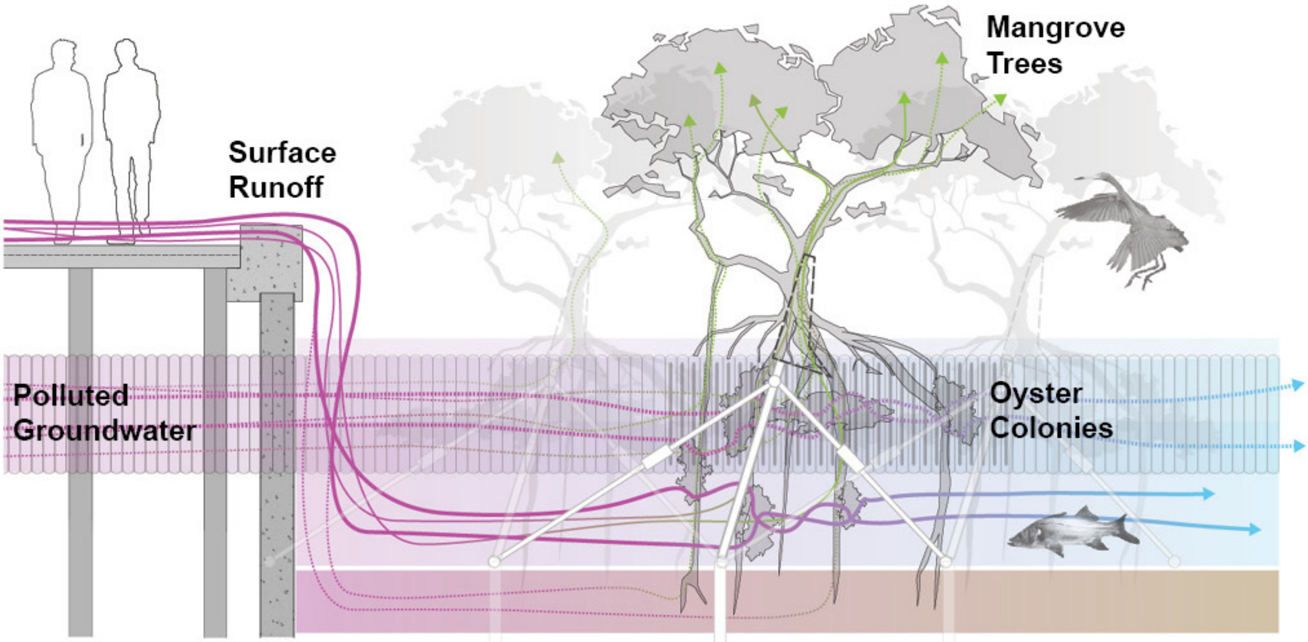
Conservationists may have concern about the impact on species and ecosystem by introducing waste streams. There exists a convincing body of research on the impact of these nutrients on mangrove ecosystems. Using the mangrove species Kandelia candel and Aegiceras corniculatum, Wong et al., (1997) found little to no effect from using mangrove wetlands as a secondary wastewater treatment.[22] A combination of inherently low nutrient and high primary production mean that mangrove ecosystems are nutrient deficit and have a large capacity to retain these contributions. Ultimately, these characteristics make the mangrove vegetation type an appropriate bioremediation candidate.

SYSTEM PROPOSAL AND METHDOLOGY

The goal of this research is to link urban runoff with vegetation growth to filter pollutants, and in the process, facilitate restoration of a coastal mosaic. This study focuses on the remediative capacity of mangrove and oysters in a combined runoff treatment arrangement for the Lemon Bay area on the west coast of Florida. Secondary ecological services of the system, such as wave dissipation and biological and aesthetic diversity, are explored through other studies on the system. In this regard, the relationship between anthropogenic pollutants and ecological productivity is used to scale the system in this design project.

The basic configuration of system components is shown below in Figure 3. A combination of surface runoff and groundwater leachate is channeled through the mangrove-oyster system, thereby promoting accelerated vegetation growth with the excess nutrients. Perforated pipes carrying runoff or septic fallout are integrated with the structural substrate to place contaminated water directly within the root zone of the trees and filtration of oysters. Tree roots and oyster communities would develop on the surface of the runoff delivery system in addition to colonizing the artificial tidal scaffold. The system's vertical dimension was designed in response to water depth in order to

Figure 3: Spatial Approximation of Nutrient Contributions to Lemon Bay from Anthropogenic Sources



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consistently place the interaction of living systems and runoff within the tidal zone to promote natural aeration. Furthermore, the seedling capture device located at the top of the scaffold is elongated to cover the tidal range, as well as near-term fluctuations in sea level.

Using this aggregated arrangement of living and artificial systems, the horizontal dimensions of the "bio-extraction" fields were scaled according to Lemon Bay nutrient loads documented by Tomasko et al., (2001, 2005). The relationship between these factors was then used to develop spatial constraints for municipal zoning codes. The goal was to provide design guidelines in the form of remediation zones for a particular municipality, however, the framework for the research can be adapted to other regions to capitalize on different species.

Calculation of Potential for Mangrove and Oyster Treatment

Anthropogenic loads primarily come from research by Tomasko et al. (2001, 2005), and the capacity for mangroves to "digest" these pollutant loads came from Rivera-Montoya (1999).[18,19,21] This paper integrates these information sets to project design solutions for the compromised Lemon Bay shoreline outlined above. By doing so, this study brings together biological and ecological sciences with design to parameterize the relationship between human development and a restorative strategy. Ultimately, the relationship between these factors is meant to give design guidelines for balancing human activities with a thriving environment.

When integrating natural systems, it's critical to recognize that different plants utilize nutrients differently. In this project, the red mangrove (rhizophora mangle) and common oyster were considered for nitrogen uptake and fixation. The relative "performance" of these two species were then used with the spatial dimensions of Lemon Bay to approximate bio-extraction fields capable of addressing the documented and projected nutrient loads.

Figure 4: "Waste as food" - schematic diagram of "BioMOP" system installation with integrated perforated pipe carrying site leachate and runoff

In terms of nutrient loading in the bay, Tomasko et al., (2005) measured 1995 nitrogen levels in Lemon Bay and established an annual contribution from anthropogenic sources. Two projections were made for increases in nitrogen loads by the year 2010. Within this study, these three different loading scenarios were used to determine the scaling of the BioMOP system. In 1995, Lemon Bay was receiving 129,713kg of nitrogen per year, or 355.38kg per day. Mangrove trees are able to remove 2.24kg per day per hectare of forest, leading to 158.65ha of mangrove forest necessary to fully remediate anthropogenic loading. This area of mangrove coverage would represent approximately 5% of the bay covered by forest. By approximating the linear shoreline available in the bay (77km, excluding minor inlets and coves), an average width of 20m would be required to attain an area capable of absorbing the loads.[23]

Simple math expounds on this to reveal the projected scenarios for 2010. If by 2010, nitrogen loads increased by 45%, an average of 30m width would be required, or 7% of the bay covered by mangroves. If levels increased by 58% by 2010, 33m width would be required or 8% of bay covered by mangroves.

Oysters are a natural partner species to mangroves, particularly on the west coast of Florida, and within the BioMOP system, the combined living systems (mangrove and oyster) would boost the performance of the mangrove only bio-extraction field. Oysters contribute to this system primarily through two means. As filter feeders, oysters are highly effective at reducing chlorophyll amounts, as well as capable of absorbing nitrogen. Through the added oyster contributions, the BioMOP system could be reduced by 15%-20% in area but would be contingent on the age, density and coverage of the bivalves.[24]

Finally, mangrove conservation areas currently exist in Lemon Bay. However, these are mostly located in zones remote from the developed shorelines, and no data exists on the role these conservation areas play in remediation of nutrients. As such, these conservation areas are excluded from the calculations, even though they may reduce the required width. Since nitrogen levels were measured in the bay with these conservation areas present, their relative contributions to nitrogen uptake in the bay may already be accounted for in the data.

RESULTS AND DISCUSSION

The initial step within this study was to parametrically link mangrove vegetation to nutrient loads to identify a remediative landscape capable of removing anthropogenic contributions from the water of Lemon Bay. The study includes oysters to further enhance the efficiency of the system with a multi-tiered bio-extraction process. By establishing a characteristic area to density ratio, the system is schematically explored for the Lemon Bay area, but could be easily adapted to fit other areas, particularly in South Florida.

Using the data on Lemon Bay outlined above, the BioMOP system was integrated within a specific site located near Stump Pass State Park at the southern end of the bay. This particular site contains a number of shoreline features common to South Florida: low to medium density construction with an array of docks and articulated shoreline to accommodate recreational boating. On the gulf and bay side, hotels and residences line the waterfront. This particular site was used to visualize the impact of integrating bio-extraction fields within a developed shoreline, using the average greenbelt width identified above.

The proposed distribution for the BioMOP system at the Lemon Bay site

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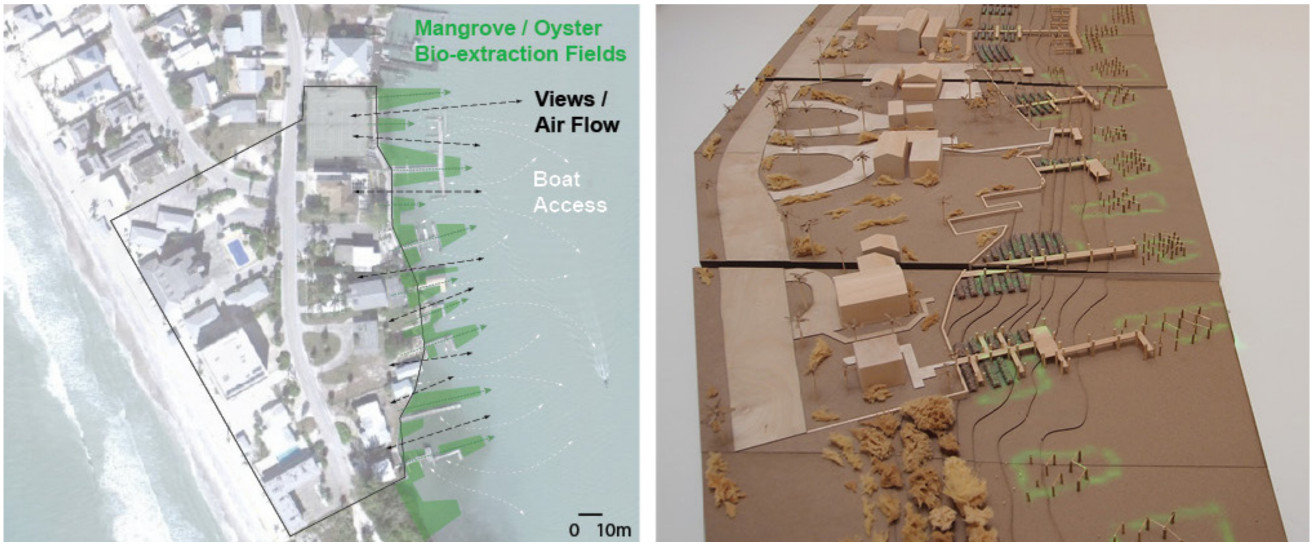

Figure 5: Site proposal and model showing areas of designated tree growth.

is shown in Figure 5 below. The average width of greenbelt is established through zones of planting, indicated by green areas in the site plan. Utilizing the existing docks as spine to the system, clustered arrangements of trees create linear extensions into the bay, with runoff delivered by conduits located under each dock. The arrangement responds to the regional economic need for recreational boating by providing dock spaces interspersed within the clustered parcels of mangrove and oysters. The installation would also contain an educational component in the form of secondary boardwalks and tidal walkways that immerse visitor in mangrove clusters to view wildlife.

The project was explored through digital and physical models to design the articulated shoreline. The physical model used a digital projection of mangrove tree growth (shown in green over zones of planting in Figure 5, right) derived from a computational forest model developed by Berger and Hildenbrandt, 2000.[25] This computational model represents red mangrove tree competition at the individual tree level, where trees compete with each other for nutrients in a 3d environment of the site. The integration of this computational forest model allowed the site proposal to include a validated simulation in the design process, a critical component in the projection of such a large-scale proposition.

CONCLUSIONS

In this work a parametric link between anthropogenic waste streams and indigenous mangrove/oyster capacity for nitrogen remediation was established. The research addressed an urban-compromised shoreline with this approach, utilizing waste streams to re-establish indigenous vegetation. Simultaneously, this project addressed the need for resilient wastewater infrastructure in tropical and subtropical coastal zones. The BioMOP system, once parameterized, appeared to address the scale of runoff within a viable distribution of trees and oysters within the context of Lemon Bay.

By capitalizing on both the natural system's inherent capacity for regenerative growth and human desires for waterfront property, an integrated solution may present opportunity to increase ecological activity through an articulated shoreline. Through this lens, the design challenge amounts to a relative balancing act between nonlinear ecosystem functions and

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simultaneous "performance" of economic development and human opportunity. These types of emerging solutions require a number of well-integrated researchers and experts to project multiple plausible outcomes for local and widespread interconnected social and environmental systems. In this regard, the conventional "all or nothing" preservation approach is in a sense antiquated, and the pending environmental collapse requires a new multidisciplinary research paradigm capable of modeling complex hybrid biomes (human-environmental). These "biomechanical" landscapes might not be easily assessed within conventional economic models but instead require advances in collaborative research to redefine "value" as a multi-faceted metric of human wellbeing and environmental health. Within this realm, this research project has a number of studies parallel to this one: computational modeling of hydrological design, including tide and wave flushing of the system and storm wave impact scenarios; biological modeling with the computational tree model; and evaluation through ecological economics of the various values of the systems (ecosystem services).

Existing urban landscapes within vulnerable coastal zones will be forced to adapt to environmental catastrophes with a number of solutions, some of which may incur significant social, economic and political adjustments. As a result, today's planning, design and construction professionals are confronted with the formidable challenge of creating conditions that enable humans to thrive without compromising the ecological function of the environment. In order to develop guidelines that promote this integrated approach, establishing a design framework that integrates the multiple biogeochemical relationships among humans and their environment is critical. Furthermore, these landscapes must target not only sustainable solutions, but developments that increase diversity and ecological processes. This approach is critical to repair the extensive damage brought on by rapid population expanse and the associated urban development. Ultimately, our civil coastal landscapes must integrate adaptable and resilient infrastructure that capitalizes on the inherent regenerative capacities of ecological systems as a benefit to humankind while simultaneously addressing the need to increase diversity and improve environmental integrity.

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