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Living shorelines enhance nitrogen removal capacity over time

Kathleen M. Onorevole*, Suzanne P. Thompson, Michael F. Piehler

University of North Carolina at Chapel Hill, Institute of Marine Sciences, 3431 Arendell Street, Morehead City, NC 28557, United States

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ABSTRACT

Living shorelines are nature-based solutions to coastal erosion that can be constructed as salt marshes with fringing oyster reefs. Each of these habitats can decrease the potential for eutrophication through increased nitrogen (N) removal via denitrification. However, the development of N cycling over time has not been studied in living shorelines. This research measured denitrification rates in a chronosequence of living shorelines spanning 0–20 years in age in Bogue Sound, NC. Analyses were conducted seasonally from summer 2014 to spring 2015 along an elevation transect through the salt marsh, oyster reef, and adjacent sandflat at all sites. Gas fluxes (N_2 and O_2) from sediment core incubations were measured with a membrane inlet mass spectrometer (MIMS) to assess denitrification and sediment oxygen demand. Fluxes of dissolved nutrients and the greenhouse gas N_2O were measured. Sediment properties, inundation frequency, oyster filtration rates, and marsh grass stem density were also quantified. There was no significant difference in denitrification rates among habitats. N removal consistently increased from the 0- to 7-year-old sites. Denitrification efficiency was always greater than 50% and positive N_2O fluxes were negligible. Our results suggest that living shorelines increase net N removal within a relatively short time period following construction, without introducing deleterious greenhouse gas emissions. This demonstrates that living shorelines can play an important role in estuarine N cycling and management.

1. Introduction

Coastal environments provide many ecosystem functions that contribute to human well-being (Costanza et al., 1997; Millennium Ecosystem Assessment, 2005). As a result, estuarine habitat loss or degradation has social and ecological consequences. Estuaries provide functions such as nursery habitat for juvenile fishes and invertebrates (Beck et al., 2001), resilience to rising sea level (Morris et al., 2002), and nutrient cycling (Jordan et al., 2011). Structured estuarine habitats also limit coastal erosion (Koch et al., 2009), which is particularly valuable given high human population densities in coastal areas. Restoration is one way to mitigate for habitat loss and reintroduce ecosystem functions, and the construction of living shorelines can be considered a specific example of oyster reef and salt marsh restoration. Living shorelines are a nature-based solution to coastal erosion. They consist of marsh vegetation with an optional fringing hard substrate: rocks, cement, or natural hard structures like oyster reefs (NOAA Living Shorelines Workgroup, 2015). Living shorelines have been shown to be more effective than bulkheads at attenuating storm impacts (Smith et al., 2017), and they incorporate natural habitats that can provide additional ecosystem services, increasing their overall value (Currin et al., 2010). Since public approval can encourage restoration (Cairns, 2000, Hackney, 2000), increased awareness of the effectiveness of living shorelines could increase their implementation. Given estimates that 14% of the US coast was hardened as of 2005 (Gittman et al., 2015), it is crucial that the environmental benefits of living shorelines are well articulated to contextualize their appropriateness as a management option.

The habitats included in living shorelines have been shown to contribute to a common goal of estuarine restoration: mitigation of nutrient loading. In nutrient-rich systems, eutrophication can lead to a host of deleterious impacts, including harmful algal blooms (Paerl and Otten, 2013), hypoxia (Hagy et al., 2004), and fish kills (Paerl et al., 1998). Nitrogen (N) is a limiting nutrient in coastal ecosystems, but NO_3^- concentration is often high due to N loading from developed watersheds (McClelland and Valiela, 1998; Bowen and Valiela, 2001), creating an imperative to manage N loads both by controlling inputs and maximizing potential for removal. The latter is imperative (Brush, 2009; Passeport et al., 2013) and can be facilitated by ecosystem engineers that promote denitrification (Gutiérrez and Jones, 2006). Denitrification is a globally important microbial pathway that removes bioavailable N from terrestrial and aquatic environments (Herbert, 1999; Sutherland et al., 2010). In shallow coastal waters, NO_3^- reduced by denitrifiers can be derived from land-based sources or

* Corresponding author.
E-mail address: konorevole@gmail.com (K.M. Onorevole).

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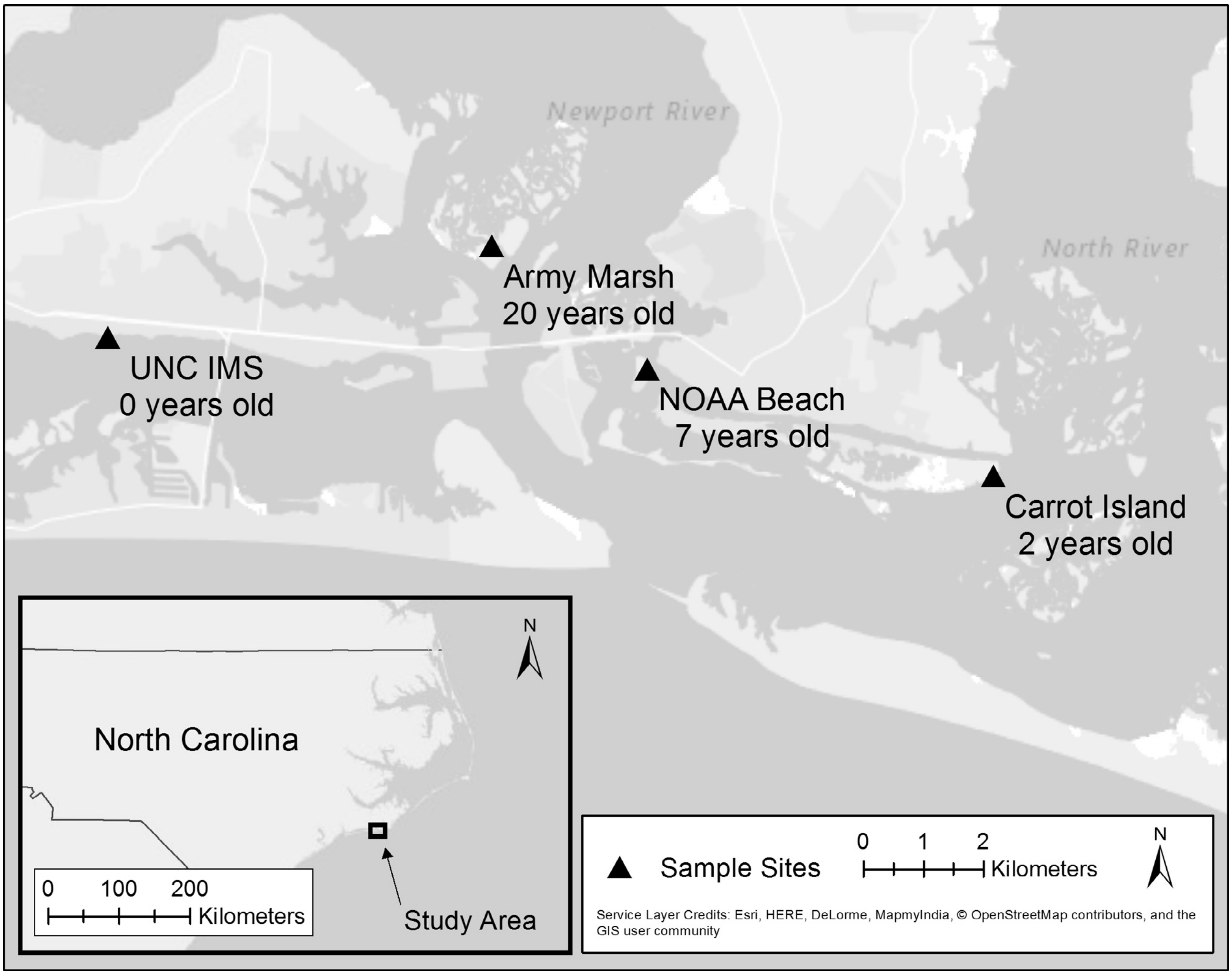

Fig. 1. Locations of the 4 sampling sites included in this study. Sites are identified by name and age, defined as years since living shorelines were constructed. Sites are located within a 13 km radius in Bogue Sound. The inset map identifies the study area within the state of North Carolina, USA.

produced by nitrification, whereby ammonium is oxidized to NO_3^-. The term "coupled nitrification-denitrification" (coupled NF-DNF) is used when the two processes are connected. Salt marshes have long been identified as important habitats for denitrification (George and Antoine, 1982; DeLaune et al., 1983), and recent work has shown that oyster reefs also facilitate high rates of denitrification (Kellogg et al., 2013; Piehler and Smyth, 2011; Seitzinger et al., 2006; Sousa et al., 2012; Pollack et al., 2013). Since living shorelines can include oyster reefs and salt marshes, they are likely to increase denitrification and consequently lower NO_3^- concentrations. However, to our knowledge, no study has directly measured N removal in living shorelines. Understanding the role of living shorelines in N cycling could lead to a more comprehensive valuation of this management option.

When designing and assessing nature-based solutions that modify N dynamics, it is also important to account for other N fluxes that are considered potential ecosystem disservices (Burgin et al., 2013; Lyytimäki and Sipilä, 2009). N_2O is a powerful greenhouse gas that is produced as a byproduct of nitrification and as an intermediate in denitrification. In estuarine environments, higher N_2O emissions are typically associated with denitrification (Dong et al., 2002), although some studies have shown that nitrification can be the main source of N_2O (de Wilde and de Bie, 2000; Ji et al., 2015). N_2O is produced via incomplete denitrification, during which it is released to the atmosphere instead of being reduced to N_2 gas. Coupled NF-DNF can reduce N_2O emissions in estuarine environments dominated by this process (Cartaxana and Lloyd, 1999; LaMontagne et al., 2003). This may have been observed because coupled NF-DNF relies on adjacent and distinct oxic and anoxic conditions, and persistent anoxia increases the likelihood of complete denitrification. Increased production of NH_4^+ can also be considered a disservice, since it provides a bioavailable N source that can promote algal growth. By measuring fluxes of N_2, N_2O, and NH_4^+, this study aimed to provide a comprehensive assessment of both beneficial and deleterious aspects of nitrogen cycling in living shorelines.

This study employed a chronosequence space-for-time replacement design to analyze living shorelines. Monitoring is time- and resource-intensive, and well-designed chronosequence studies can provide the benefits of long-term monitoring without the expense (Hutto and Belote, 2013). Data from chronosequences can be used to construct restoration trajectories, which are theoretical frameworks that visualize change in an environmental parameter over time (Kentula et al., 1992). Although the concept of restoration success remains a contentious one (Kentula, 2000; Ruiz-Jaen and Mitchell Aide, 2005; Zhao et al., 2016), restoration practitioners have been advised to identify specific habitat functions as goals (Hackney, 2000, Simenstad and Cordell, 2000). Restoration trajectories can illustrate a range of development pathways for a chosen function based on management decisions and environmental stressors (Testa et al., 2017), which can provide a useful framework for evaluating projects.

The goal of this study was to evaluate the development of N removal

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