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Research article

A spatial model to improve site selection for seagrass restoration in shallow boating environments

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ABSTRACT

Due to widespread and continuing seagrass loss, restoration attempts occur worldwide. This article presents a geospatial modeling technique that ranks the suitability of sites for restoration based on light availability and boating activity, two factors cited in global studies of seagrass loss and restoration failures. The model presented here was created for Estero Bay, Florida and is a predictive model of light availability and boating pressure to aid seagrass restoration efforts. The model is adaptive and can be parameterized for different locations and updated as additional data is collected and knowledge of how factors impact seagrass improves. Light data used for model development were collected over one year from 50 sites throughout the bay. Coupled with high resolution bathymetric data, bottom mean light availability was predicted throughout the bay. Data collection throughout the year also allowed for prediction of light variability at sites, a possible indicator of seagrass growth and survival. Additionally, survey data on boating activities were used to identify areas, outside of marked navigation channels, that receive substantial boating pressure and are likely poor candidate sites for seagrass restoration. The final map product identifies areas where the light environment was suitable for seagrasses and boating pressure was low. A composite map showing the persistence of seagrass coverage in the study area over four years, between 1999 and 2006, was used to validate the model. Eighty-nine percent of the area where seagrass persisted (had been mapped all four years) was ranked as suitable for restoration: 42% with the highest rank (7), 28% with a rank of 6, and 19% with a rank of 5. The results show that the model is a viable tool for selection of seagrass restoration sites in Florida and elsewhere. With knowledge of the light environment and boating patterns, managers will be better equipped to set seagrass restoration and water quality improvement targets and select sites for restoration. The modeling approach outlined here is broadly applicable and will be of value to a large and diverse suite of scientists and marine resource managers.

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1. Introduction

Seagrass ecosystems are extremely productive and provide numerous ecological services valued globally at 28,916 2007US$/ha/yr (Orth et al., 2006; Costanza et al., 2014). One of the ecological services seagrasses provide is structural habitat for a variety of fisheries species, as well as other ecologically important taxa (Beck et al., 2001; Marbà et al., 2006). Seagrass leaves also dampen wave energy and reduce water flow, thus promoting particle deposition and improving water clarity (Bos et al., 2007; Fonseca et al., 2000; Marbà et al., 2006; van Katwijk et al., 2010). The dense network of rhizomes and roots associated with many seagrass species facilitates sediment stabilization and healthy seagrass beds that can protect adjacent shorelines from extreme tidal and storm events (Green and Short, 2003). Seagrass beds also play an integral role in nutrient cycling, and carbon sequestration in particular (Hemminga et al., 1991; Duarte and Chiscano, 1999; Fourqurean et al., 2012).

Much seagrass has been lost due to development associated with human population pressures at the land ocean interface (Orth et al., 2006; Walker et al., 2006; Waycott et al., 2009). Development

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often negatively impacts water clarity in estuarine and shallow, coastal waters (Waycott et al., 2009). These areas are often subject to high sediment input and increased nutrient loading, which, in turn, increase turbidity and promote algal growth; both of which lead to a decrease in light available for seagrasses growth (Tomasko and Lapointe, 1991; Lapointe et al., 1994; Ralph et al., 2006; Bricker et al., 2008). The link between eutrophication and loss of seagrasses is well established (Antón et al., 2010).

However, seagrass light requirements are known to vary by species, location, and light history (Choice et al., 2014). A thirteen year study of eight Florida Gulf Coast systems determined the light requirement for *Thalassia testudinum* to be between 18 and 25% of surface irradiance; between 25 and 27% for *Halodule wrightii*; and between 8 and 16% for *Syringodium filiforme* (Choice et al., 2014). On Florida's east coast, Steward et al. (2005) found that the minimum annual light requirement for all seagrass species in the Indian River Lagoon was 20± 14% of surface irradiance and average annual light requirement was 33± 17% of surface irradiance. In Charlotte Harbor, about 55 km north of Estero Bay where our study took place, Tomasko and Hall (1999) determined that, on average, 23% of surface light reached *Thalassia testudinum* beds throughout the year and Janicki Environmental (2010) determined that a minimum of 25% of surface light should reach the bottom for healthy seagrass to occur. The variation in light requirements cited here indicates that a great deal of uncertainty surrounds the minimum level of surface light required for seagrass survival and growth. Additionally, these findings suggest that understanding spatial variation in seagrass light requirements is key to successful seagrass restoration efforts.

Another threat to seagrass is the continued growth in recreational boating which leads to increases in direct and indirect impacts on seagrass (Sargent et al., 1995; Dawes et al., 1997; Kenworthy et al., 2002). In a global analysis of seagrass restoration projects, damage to seagrass from boats/vessels was listed among the causes of restoration failure (van Katwijk et al., 2016). Cullen-Unsworth and Unsworth (2016) listed the reduction of impacts from boats among their eleven strategies for enhancing seagrass resilience worldwide. In Florida, Yarbro and Carlson (2013) interviewed staff who were involved in seagrass management and monitoring programs and, of the 24 Florida regions covered in their comprehensive review, 16 included management recommendations to monitor, minimize, and/or restore seagrass damage caused by propeller scarring.

Direct negative impacts to seagrass from boats occur when vessel hulls, propellers, anchors, and anchor/mooring chains make physical contact with seagrasses and result in scarring, prop dredging, and blowouts (Walker et al., 1989; Kirsch et al., 2005; Uhrin et al., 2011; La Manna et al., 2015). Once damaged, weakened and/or fragmented, seagrass beds are further vulnerable to storm events, which can delay their recovery indefinitely (Whitfield et al., 2002; Hammerstrom et al., 2007). Boat wakes and waves that disturb bottom sediments increase turbidity, reduce water clarity, and can also decrease the abundance and richness of epifauna on seagrass blades, particularly in shallow water (Koch, 2002; Bishop, 2008).

In addition to the combined impacts of coastal development and boating, challenges to restoration are also associated with the occurrence of seagrasses on sovereign submerged land (Hotaling et al., 2011). In Florida, the state is obligated to protect the public's interests in sovereign submerged lands: both in using them for boating, fishing, and swimming, and in safeguarding the associated natural resources that make such activities enjoyable. These interests, however, often conflict as boating/fishing activities can damage seagrasses if not done responsibly or properly. To help maximize achievement of both interests, we developed a site selection model to aid seagrass restoration efforts.

Identifying sites suitable for seagrass restoration is challenging and inappropriate site selection is the most common recurring failure in seagrass restoration (van Katwijk et al., 2016, 2009; Fonseca, 2011). Decades of experiential knowledge has helped refine site selection guidelines (van Katwijk et al., 2009; Fonseca et al., 1998) and this effort continues (van Katwijk et al., 2016). At a minimum, to be considered for seagrass restoration, an area must meet the following three criteria: historic presence of seagrass, loss due to human impact, and the removal of the impact (Fonseca et al., 1998). The model presented here was developed for Estero Bay, which has a historic presence of seagrass and documented seagrass loss attributed to human activities. Managers have taken steps to “remove the impact” by improving water quality and preventing motorized vessel impacts, making Estero Bay a candidate for restoration.

The Charlotte Harbor National Estuary Program (CHNEP) has established a restoration target of 1481 ha for Estero Bay based on the maximum historical extent of seagrass beds (Yarbro and Carlson, 2013). The state and the local community have taken several steps to improve water quality that will help to reach this target. These steps include, acquiring land to form a buffer preserve around the bay, a fertilizer ordinance that prohibits the application of fertilizer during the rainy season and establishes a 10-foot buffer around water bodies where fertilizer cannot be applied, and total maximum daily loads for pollutants. A general permit granted to the West Coast Inland Navigation District by the Florida Department of Environmental Protection provides for the marking and enforcement of two No Internal Combustion Motor Zones (NICMZs) in Estero Bay, totaling 235 ha, for the protection and restoration of propeller scarred seagrass beds (Florida Administrative Code, 2010). This is necessary as the Florida Fish and Wildlife Research Institute's Seagrass Integrated Mapping and Monitoring Program (SIMM) cites propeller scarring of seagrass in Estero Bay as a significant and ongoing problem, causing “large negative changes in seagrass” (Yarbro and Carlson, 2013). There is extensive scarring of seagrass beds in the study area with 48.7% (451 ha) demonstrating some level of scarring: light 2.5%, moderate 11.5%, and severe 34.7% (Madley et al., 2004).

Factors that affect seagrass restoration at the site level include but are not limited to emersion and desiccation effects; bioturbation; sediment thickness; pore-water chemistry; stability; natural recolonization; nutrient limitation or overload; light requirements and light attenuation characteristics of the site; salinity and temperature tolerances; and waves and current speed. In Estero Bay, managers determined light attenuation and boating to be the variables most limiting to seagrass (Yarbro and Carlson, 2013). Recently quantitative models have been used to model these types of variables. For example, a spatial predictive model was created for *Zostera marina* based on historical information, scientific literature, field measurements and test plantings (Short et al., 2002). The model findings were consistent with previously reported guidelines; greater restoration success was achieved in shallow, gently sloping, sheltered areas (Bekkby et al., 2008). A habitat suitability map was created for *Zostera marina* and *Zostera noltii* in the Dutch Wadden Sea based on duration of exposure, current velocity, wave exposure, salinity, and ammonium load (Bos et al., 2005). A 2 km $\times$ 2 km GIS based model of the presence and spatial distribution of seagrass within the Great Barrier Reef World Heritage Area, identified tidal range and relative wave exposure as the primary drivers of seagrass distribution from among eight environmental variables (Grech and Coles, 2010). Valle et al. (2011) used topographic variables, sediment characteristics, and hydrodynamic variables to predict habitat suitability for *Zostera noltii*.

Here, we present a GIS-based site selection model that integrates light, bathymetry, and boating activity to rank sites

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