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THEME SECTION

Eelgrass recovery induces state changes in a coastal bay system

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CONTENTS

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INTRODUCTION

Eelgrass recovery in the coastal bays of the Virginia Coast Reserve, USA

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ABSTRACT: Coastal bay systems are prominent features of coastlines on nearly all continents and are vulnerable to long-term environmental changes related to climate and nutrient over-enrichment. Eelgrass *Zostera marina* disappeared in the 1930s from the coastal bays of the Virginia Coast Reserve, USA, primarily due to a wasting disease and the effects of a hurricane. It has been re-established recently as a result of a large-scale seeding and restoration effort. The contributions to this Theme Section provide the most comprehensive account available of large-scale recovery of an eelgrass ecosystem, the consequences of the state change from a bare-sediment system to eelgrass dominance, and projections of meadow resilience to future climate change scenarios.

KEY WORDS: *Zostera marina* · Coastal restoration · State change · Regime shift

Coastal bay systems are prominent features of coastlines on nearly all continents, and although their watersheds are small relative to large river-fed estuaries, they are as vulnerable to long-term environmental changes related to climate and nutrient over-enrichment (McGlathery et al. 2007). In these shallow-water systems, where most of the seafloor is in the photic zone, seagrass and benthic algae dominate metabolism and nutrient cycling, play a critical role in stabilizing the coastline, and provide habitat for important components of the fauna. Long-term trends in seagrass abundance and distribution indicate that the rate of habitat loss is accelerating worldwide, due to degraded water quality, disturbance and disease; this is accompanied by a loss of ecosystem services (Orth et al. 2006a, Waycott et al. 2009, Short et al. 2011). There has been some success in large-scale restoration efforts to mitigate these losses, but not enough to reverse the declining trends globally (Waycott et al. 2009).

The Virginia Coast Reserve

The coastal bays of the Virginia Coast Reserve (VCR) are renowned for their local, regional, and global value to migratory birds (Watts & Truitt 2001) and diverse marine life, as well as for historically supporting fisheries of significant commercial value (Barnes & Truitt 1998). The VCR coastal bays suffered a catastrophic ecosystem state change in the 20th century, primarily due to a wasting disease that devastated *Zostera marina* (eelgrass) and a hurricane in 1933 that likely eliminated remaining populations.

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The state change from *Z. marina* to an 'unvegetated' bottom dominated by benthic algae resulted in the loss of critical ecosystem services, including the provision of food and nursery habitat for numerous avian and marine species such as the bay scallop *Argopecten irradians*. While *Z. marina* eventually rebounded from the pandemic decline in the Chesapeake Bay and in many coastal bays along the eastern seaboard of the United States (Cottam & Munro 1954), there are no records of *Z. marina* in the VCR coastal bays until the mid-1990s (Orth et al. 2006b).

What makes the coastal bays of Virginia unique, and what has been important to the restoration of *Zostera marina*, is that they represent systems that receive relatively little impact from human activities. The VCR is a Long Term Ecological Research (LTER) site that is part of a network of 26 sites representing diverse marine and terrestrial ecosystems (www.lternet.edu). At the VCR, ongoing studies for 2 decades examining physical, biogeochemical and biological aspects of the coastal bays in the absence of *Z. marina* (e.g. McGlathery et al. 2001, Anderson et al. 2003, Tyler et al. 2003) set the stage for understanding the consequences of the state change back to eelgrass dominance from the unvegetated state. Long-term data from the VCR LTER show that watershed nutrient loading to the coastal bays is low and that water quality with respect to nutrients and chlorophyll has remained high for the last 2 decades (www1.vcrlter.virginia.edu/home1/?q=data_wq). In 1970, the VCR was established as a reserve by The Nature Conservancy and later was recognized as a Man and the Biosphere Reserve, creating a legacy of conservation and stewardship. The VCR is both a model system for understanding the dynamics of *Z. marina* recovery where habitat quality is high, and an important reference point for the more heavily-impacted systems that are typical of coastal regions (Kennish & Paerl 2010).

Return of a foundation species

Restoration of *Zostera marina* with seeds in this system has been very successful since the late 1990s. Approximately 1700 ha of bottom in 4 lagoons that had abundant *Z. marina* prior to its demise again support robust populations (Fig. 1). While there has been no definitive answer as to why *Z. marina* never recovered from the 1930s demise, recent work provides strong support that recruitment limitation (primarily seeds), and not increased turbidity following the loss of *Z. marina* (Peterson & Lipcius 2003), was the primary reason why *Z. marina* did not recover. This conclusion is supported by the recent success of restoration by seeding, monitoring that revealed good water quality, physical modeling of sediment suspension and water column light attenuation (Lawson et al. 2007), and by a more complete understanding of the biology and ecology of this species (Moore & Short 2006), especially its dispersal dynamics (Harwell & Orth 2002).

The change from an unvegetated state to one with dense and extensive *Zostera marina* populations has provided a unique opportunity to understand the central role of *Z. marina* as a foundation species in temperate shallow coastal systems. Throughout this theme section we use the term 'restoration' in the broadest sense. While this term has generally been applied to systems that have been altered due to anthropogenic activities, we adopt this term for our work here based on the comment in Elliott et al.

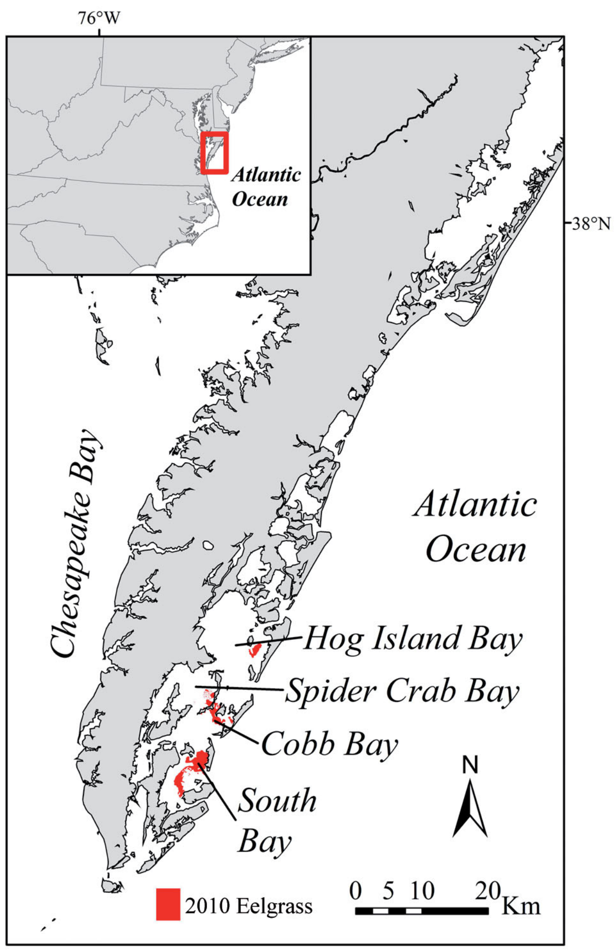

Fig. 1. Delmarva Peninsula and sites of eelgrass restoration (red)

(2007, p 357) 'we recommend that producing new habitat can be termed creation or enhancement whereas re-creating habitat that was present within historical records, no matter how old, should be termed restoration.'

Contributions to this Theme Section

The studies in this Theme Section cover a broad and comprehensive range of topics. Orth et al. (2012) describe the rapid changes in *Zostera marina* distribution initiated by seeding and by natural recruitment processes that have facilitated recovery. By continuously monitoring water quality, they show how one meadow modulated water clarity and altered the sediment as it developed and expanded. Marion & Orth (2012) investigate the processes leading to the low initial seedling establishment noted in Orth et al. (2012) through a manipulative field experiment that addressed the relative importance of germination failure and seedling loss during the winter. They show that some of the key processes in recruitment and restoration of *Z. marina* involve physical sediment–seedling interactions rather than seed germination. McGlathery et al. (2012) compare sites from 0 (unvegetated) to 9 yr after seeding and show the restoration of key ecosystem services such as primary productivity, carbon and nutrient sequestration, and sediment deposition. However, their results indicate that none of the parameters monitored reached an asymptote after 9 yr, indicating that more time is required for full restoration of these ecosystem services. They also identify the depth limit (1.6 m) for eelgrass populations in the coastal bays. Using microsatellite markers, Reynolds et al. (2012) show that the high genetic diversity in donor beds from Chesapeake Bay is maintained in meadows restored by seeding in the Virginia coastal bays. Cole & McGlathery (2012) found that nitrogen fixation increased as the meadows aged, with older beds fixing almost 3 times more nitrogen than younger meadows and 30 times more than bare sediment. Moore et al. (2012) compare water quality conditions associated with *Z. marina* populations in the coastal bays and in nearby areas in the lower Chesapeake Bay, where *Z. marina* has either declined or remained static over the same time period. Their results indicate that lower summertime water temperatures and lower light attenuation interact to both increase the proportion of light available for *Z. marina* photosynthesis and decrease *Z. marina* community light requirements at the coastal bay sites. They suggest that the greater tidal range and proximity of the coastal bays to cooler ocean waters ameliorates the stress from high air temperature periods during the summer. Using controlled microcosm experiments, Lawson et al. (2012) show that at low shoot densities *Z. marina* increases sediment suspension due to the horizontal deflection of flow around eelgrass shoots, but that past a threshold density, eelgrass reduces sediment suspension. In field studies, Hansen & Reidenbach (2012) quantify the relative effects of meadow structure on tidal currents, waves, and near-bed turbulence, and the resulting sediment suspension: expansion of *Z. marina* within the coastal bays has shifted the seafloor from an erosional to depositional environment, leading to enhanced light penetration through the water column and creating a positive feedback for *Z. marina* growth. Carr et al. (2012) build this positive feedback into a coupled vegetation-growth hydrodynamic model to investigate *Z. marina* stability and leading indicators of ecosystem shift under future scenarios of sea level rise and warmer sea temperatures. Their model identifies the emergence of alternative stable states (vegetated vs. barren bottom) with a maximum depth threshold based on water clarity and growth conditions. Their results also indicate that *Z. marina* meadows in these coastal bays have limited resilience to increases in water temperature predicted from current climate change models, and agrees with field evidence presented by Moore et al. (2012).

Perspectives

The contributions to this Theme Section provide the most comprehensive account available of large-scale recovery of a seagrass ecosystem, the consequences of the state change from a bare-sediment system to eelgrass dominance, and projections of meadow resilience to future climate change scenarios. This is a model system to understand state change dynamics in shallow coastal bays, and future work will include trophic dynamics, restoration of bay scallops, and landscape analysis.

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