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SPECIAL ISSUE: CONCEPTS AND CONTROVERSIES IN TIDAL MARSH ECOLOGY REVISITED

Concepts and Controversies in Tidal Marsh Ecology Revisited

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Tidal salt marshes are an essential part of coastal seascapes. These intertidal habitats, and the plants that colonise them, confer structural and functional characteristics that are essential for the broader function of estuarine ecosystems, and the marine systems beyond, but also provide crucial protection for coastal infrastructure. One of the most widely recognised services provided by tidal marshes is the support of fish, crustacean, and mollusc species that are exploited through fisheries. This support takes many forms, such as the provision of key habitat for juveniles and adults alike, improved water quality resulting from the filtration and cleansing functions that these habitats perform, and through primary production and trophic provisioning which supports growth and productivity of exploited species. Early descriptors of these processes included the seminal contribution by Teal (1962) who demonstrated that primary production (P) in Georgia salt marshes was greater than community respiration (R), P/R > 1, an observation that led him to assume that excess production was "outwelled" to the greater estuary and coastal zone. Not long after, Gunter (1967) noted that the vast majority of commercial finfish and shellfish had "estuarine-dependent" early life stages, and this concept was soon extended to include tidal salt marshes that serve as critical "nurseries" for the young of marine transient species (e.g. Weinstein 1979). Similarly, Haines (1979) revised the early salt marsh paradigm to include not only in situ processes, but the export of marsh production to the greater estuary and coastal environs through the flow of organic matter and nutrients and organisms, the latter described as "trophic relays" (Kneib 1997). These functional linkages (or "connectivity" as we have come to call it) have been highlighted in many studies in the period since.

Two watershed workshops have progressed research on tidal salt marshes: the first in 1958 (Ragotszkie et al. 1959) and the second in 1998 (Weinstein and Kreeger 2000). During the > 50 years covered by these two events, research has focussed on diverse themes within the discipline such as biogeochemistry, outwelling, nutrient exchange, as well as broader questions of tidal marsh structure and function. Over this period, various controversies have emerged, and some of these have been resolved, but importantly the services provided by these systems in support of fisheries species have remained a central theme of investigation within the field for the past 70 years. As our knowledge base has continued to increase, so has our appreciation of the inherent complexity of tidal marsh systems and their connections with the broader coastal seascape.

The 1998 symposium laid a solid foundation for the two decades of research that followed, but the twenty-first century has brought with it an amplification of historic threats, as well as novel challenges, and new ideas and opportunities for conserving and rebuilding tidal marsh systems and preserving their important role in food security into the future. However, as the human population continues to grow, tidal marsh systems have increasing pressures, and the areal coverage of these environments has greatly reduced. The recognition of tidal salt marshes as essential components of coastal economies has led to increased efforts to protect against further loss and/or degradation of these habitats. Ecological restoration has a foundation in ecological fidelity (Higgs 1997) and the human dimensions (Cairns Jr. et al. 1977), but because human activities in the Anthropocene have pushed the earth

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Figure 1 Delegates attending the Coastal and Estuarine Research Federation 25th Biennial Conference Workshop *Concepts and Controversies in Tidal Marsh Ecology Revisited*, 2–3 November 2019, Dauphin Island Sea Lab, Alabama. Delegates included: (seated, left to right) Jennifer Rehage, Justin Lesser, Ryan Rezek, Matt Taylor, Mike Weinstein, Ronald Baker, Carolyn Currin, Linda Deegan, Candy Feller, Ken Able; (standing, L-R) W. Ryan James, Patrick Rayle, Felicity Hardcastle, Joseph Smith, Alyssa Frank, Lucy Goodridge Gaines, Sarah Ramsden, Christopher Henderson, Ed Kim, James Pahl, Charles Martin, Rod Connelly, Blair Morrison, James Reinhardt, Janelle Goeke, Ashley McDonald, Scott Alford, Denise Colombano, Shelby Ziegler, Eric Sparks, Just Cebrian, Sarah Crosby, Philine zu Ermgassen, Lorie Staver, Caitlin Alcott, Nathan Waltham, Mark Risse, Myriam Barbeau, Si Simenstad, Kate Dodds, Tom Minello, Matt Kimball, Lawrence Rozas, Jeff Ollerhead, Matt Kenway, Sharil Deleon, Ben Gilby, Angela Garelick, James Nelson, Debbrota Mallick, Catherine McLuckie, Gregory Norris. Photo credit: R. Eugene Turner. Note that not all delegates were present for this picture

system outside of its normal operating range, not only do many ecosystems differ in pattern and process from those in the past, but by increasing necessity, the ecosystem concept itself is becoming framed in the context of climate change, land use, invasive species, reduced biodiversity, and other effects of human endeavours (Steffen et al. 2006). As a consequence, the challenges of conservation, restoration, and rehabilitation of tidal salt marsh ecosystems have reached new heights of complexity and urgency.

While the role of healthy estuaries in supporting productive ecosystems and sustainable fisheries maintains an impetus for science-based conservation and restoration of tidal wetlands, a new paradigm is needed to achieve this alongside the challenges posed by increasing urbanisation and climate variability. In addition, increasing attention to the triple-bottom-line (environmental-economic-social outcomes) in resource management creates a need for valuation of ecosystem services and economic/social justification for habitat conservation. Alongside these developing themes, many of the scientists who have been instrumental in this field over the past 30–40 years, have reached, or are reaching, the end of their careers. Consequently, another meeting-of-the-minds was justified, to capture the thoughts and insights of these scientists, and meld this with the ideas of the younger scientists entering the field. Thus, the symposium "Concepts and Controversies in Tidal Marsh Ecology Revisited" was conceived as an intergenerational meeting of tidal marsh ecologists examining marsh support of fisheries, and was held as part of the 2019 25th Biennial Coastal and Estuarine Research Federation (CERF) meeting in Alabama (Fig. 1). This special issue captures some of the key outcomes of this successful workshop.

Presentations, discussions, and deliberations lead to the proposal of six focal areas that captured contemporary risks or opportunities for research and development. These are outlined in detail within six core perspectives articles, which appear throughout the special issue. These articles open with Ziegler et al. (2021), who provide a foundational appraisal of the key drivers of variation in tidal marsh structure and function that is observed in the literature. This is important, since tidal marsh studies are necessarily place based, but advancement of our understanding of these systems at a conceptual level relies on drawing out common themes in the structure and function of these systems across different geographic locations, at the same time as identifying the proximal factors that are responsible for this geographic variability. This is essential for predicting, within a geographic context, the consequences of the pervasive threats that affect tidal marshes across the world (discussed further in Gilby et al. 2020 and Colombano et al. 2021b). Within this context, Kimball et al. (2021) outline recent technological advances that will aid the study of tidal marsh systems, and how the resultant data streams may be integrated and exploited to ask "big questions" about the structure and function of marsh systems, through the lens of services in support of exploited species.

Two contributions deal explicitly with the contemporary threats faced by tidal marsh ecosystems. Gilby et al. (2020) introduce the diverse suite of stressors that can (and are) affecting tidal marsh seascapes. Specifically, stressors such as climate change, sea level rise, urbanization, eutrophication,

fishing, and invasive species can have interactive effects, with implications at both the local and bioregional scale. Climate change (and its associated perturbations) represents the most existential threat to the services we require from tidal marsh ecosystems and is addressed in the context of exploited species in Colombano et al. (2021b). Measuring, planning for, and effectively managing the interactive suite of impacts associated with climate change creates the need for cross-disciplinary research, but the influence of climate-derived stressors is likely to particularly impact on the provisioning of coastal nekton (including fisheries species) by tidal marshes. Some of the concepts introduced by Colombano et al. (2021b) and Gilby et al. (2020) are exemplified in Able (2021), which provides an observational treatise describing the effects of sea level rise over a period of almost 100 years.

Two contributions tackle the prospects for restoration from two different perspectives. Waltham et al. (2021) examine the key features of tidal marsh restoration efforts and highlight specific factors that require careful consideration in restoration endeavours. zu Ermgassen et al. (2021b) consider how our knowledge of the ecosystem services provided by tidal marshes can aid restoration efforts, and the business case for conservation, restoration, and assisted adaptation to climate change. The fisheries-specific consequences of many of the issues dealt with in this suite of contributions are synthesised in Baker et al. (2020), with the core recommendation that continued targeted research in these areas is required to support policy makers to adequately manage threats and stressors and maintain the marsh-derived ecosystem services that support the productivity of exploited species.

These perspective articles are interspersed with contemporary case studies in support of the concepts outlined above. The structural and functional characteristics of tidal marshes are considered in several studies (James et al. 2020; Jones et al. 2020; Curran et al. 2021; Kimball and Eash-Loucks 2021; Smith and Pellew 2021), supported with examples that apply contemporary approaches for exploring these characteristics (Bennett et al. 2020; Baker et al. 2021; Colombano et al. 2021a; zu Ermgassen et al. 2021a). System change within tidal marshes is considered in the context of factors that impact their health, resilience and productivity (Crosby et al. 2021), and the implications for marsh nekton (Harris et al. 2020). The special issue concludes with some contemporary analyses of restoration endeavours and the economic outcomes that may be derived from repair and factors that contribute to success (Armitage 2021; Weinstein et al. 2021).

Taken together, these contributions provide a contemporary treatise on the continuing development of tidal marsh ecology in the twenty-first century, highlighting issues, arenas for progress, and strategies for repair and conservation within the social and economic framework on which our society depends. Much work has been done to address the "controversies" that existed in this discipline, but the "concepts" continue to evolve as our knowledge base increases and further threats to these systems emerge. However, it is more than the knowledge base that is changing, and certainly not in a comparably encouraging direction. As pointed out earlier, and notably elucidated by Gilby et al. (2020), the human-induced challenges to coastal ecosystem functioning will require more intense and integrated science and rehabilitation if we are to even sustain tidal marshes. The increasingly concerning prognoses of our changing coast imply that our documentation of unique case studies may fail to provide the comprehensive guidance required to accommodate the more accelerating threats. Albeit insightful, the current literature continues to predominantly represent "opportunistic" insights into environmental processes and rates that are driving tidal marsh response to ever-pressing climate change and coincident threats. Even those cases that more strategically address climate change, are typically insular in the absence of a coastal landscape or watershed context and lead to additional questions such as how sustainable are the extant tidal marshes versus viable opportunities for upland migration, what are the conditions constraining such adaptability, and where are strategic opportunities for adaptation versus landscape resistance? A complicating dilemma that also needs to be bridged is moving beyond the opportunistic acceptance of research and restoration sites, to more scientifically strategic comparison of sites that are hypothesized to vary in the proximal-to-landscape factors that may affect sustainability and restoration. Despite the "mature" messages and recommendations from this august contingent of aged scientists, and the enthusiasm shown by the younger contingent, it is evident that the science is still short of forming comprehensive assessments in the face of rapidly emerging threats. This remains an emergent and pressing challenge for the next generation of tidal marsh researchers.

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