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Drivers of Change in Shallow Coastal Photic Systems: An Introduction to a Special Issue

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Abstract Coastal ecosystems are characterized by relatively deep, plankton-based estuaries and much shallower systems where light reaches the bottom. These latter systems, including lagoons, bar-built estuaries, the fringing regions of deeper systems, and other systems of only a few meters deep, are characterized by a variety of benthic primary producers that augment and, in many cases, dominate the production supplied by phytoplankton. These "shallow coastal photic systems" are subject to a wide variety of both natural and anthropogenic drivers and possess numerous natural "filters" that modulate their response to these drivers; in many cases, the responses are much different from those in deeper estuaries. Natural drivers include meteorological forcing, freshwater inflow, episodic events such as storms, wet/dry periods, and background loading of optically active constituents. Anthropogenic drivers include accelerated inputs of nutrients and sediments, chemical contaminants, physical alteration and hydrodynamic manipulation, climate change, the presence of intensive aquaculture, fishery harvests, and introduction of exotic species. The response of these systems is modulated by a number of factors, notably bathymetry, physical flushing, fetch, sediment type, background light attenuation, and the presence of benthic autotrophs, suspension feeding bivalves, and fringing tidal wetlands. Finally, responses to stressors in these systems, particularly anthropogenic nutrient enrichment, consist of blooms of phytoplankton, macroalgae, and epiphytic algae, including harmful algal blooms, subsequent declines in submerged aquatic vegetation and loss of critical habitat, development of hypoxia/anoxia particularly on short time scales (i.e., "diel-cycling"), fish kills, and loss of secondary production. This special issue of *Estuaries and Coasts* serves to integrate current understanding of the structure and function of shallow coastal photic systems, illustrate the many drivers that cause change in these systems, and synthesize their varied responses.

Keywords Coastal lagoons · Coastal bays · Bar-built estuaries · Natural and anthropogenic stressors · Drivers of change · Primary and secondary production · Microbial and hydrological processes · Algal blooms · Climate change effects · Eutrophication · Conceptual model · Restoration

Shallow Coastal Photic Systems

Estuaries and other nearshore coastal systems are among the most productive on the planet (Schelske and Odum 1962; Whittaker and Likens 1975). High rates of primary production are sustained by numerous nutrient sources, including anthropogenically enhanced rates of watershed nutrient loading from rivers, overland flow, and groundwater; subtidal advection of relatively nutrient-rich bottom water from offshore; elevated rates of atmospheric nutrient deposition; and rapid internal recycling of nutrients particularly from sediments under seasonally elevated temperatures (Fig. 1) (Nixon 1981, 1995; Kemp and Boynton 1984; Boynton et al. 1995; Nixon et al. 1995, 1996). Primary production in these systems is enhanced due to shallow depths and even shallower mixed layer depths due to freshwater-induced stratification which tends to retain phytoplankton within a shallow photic zone (Fisher et al. 1988; Boynton and Kemp 2000) and enhanced input of energy which serves to break down barriers to diffusion and enhance benthic–pelagic coupling (Schelske and Odum 1962; Nixon 1988).

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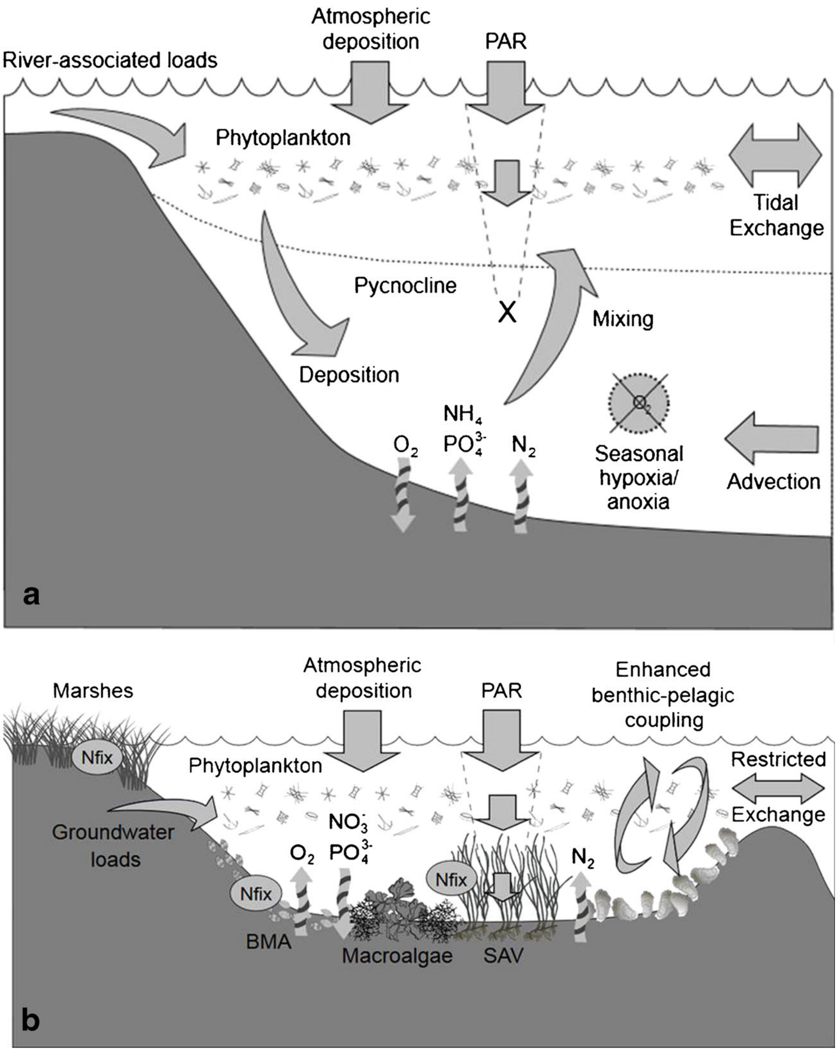

Fig. 1 Conceptual models illustrating the key differences between **a** deep, plankton-based estuaries and **b** shallow coastal photic systems. **a** Deep systems are characterized by phytoplankton blooms typically fueled by watershed nutrient inputs; these can include harmful algal blooms (HABs) in impacted systems. These blooms tend to sink below the pycnocline to the bottom where they fuel water column and sediment oxygen consumption, nutrient remineralization, and in many cases, seasonal hypoxia/anoxia. Remineralized nutrients are subsequently mixed back to surface waters. Sediment denitrification removes a portion of biologically available nitrogen as N_2 gas. **b** Light penetration to the bottom of shallow photic systems fuels multiple primary producers, including phytoplankton (and HABs), benthic microalgae (BMA), macroalgae, and submerged aquatic vegetation (SAV) and its epiphytes. Production is typically fueled by groundwater-derived nutrients and N fixation in marshes, sediments/BMA, and epiphytes on SAV. Benthic production often reverses the typical sediment fluxes, with a net release of oxygen and uptake of inorganic nutrients. Denitrification still removes some fixed nitrogen. These systems are often characterized by restricted tidal exchanges and the lack of stratification results in enhanced benthic-pelagic coupling. While both deep and shallow systems are often fringed by emergent tidal marshes (both salt and fresh), shallow systems tend to have greater connectivity between subtidal areas and adjacent marshes and greater ratios of marsh to open water area; marshes are therefore highlighted in **b** rather than **a**. These marshes exchange materials with the adjacent systems and provide a number of ecosystem services. Similarly, benthic fauna (especially filter feeders) have a greater connection to the system in shallow environments and are therefore highlighted in **b**; however, filter feeders and other macrobenthos are certainly abundant in deeper estuaries. *Symbols* courtesy of the Integration and Application Network (IAN), University of Maryland Center for Environmental Science (ian.umces.edu/symbols/). *Diagrams* created using the IAN Online Conceptual Diagram Creator

These high rates of primary production, together with allochthonous inputs of fixed carbon from surrounding watersheds and adjacent tidal marshes, fuel a food web that is typified by high rates of secondary production and fisheries yields (Nixon 1982; Houde and Rutherford 1993; Nixon and Buckley 2002; Breitburg et al. 2009). This secondary production is further enhanced by tight benthic–pelagic coupling due to rapid sinking of phytoplankton blooms, efficient filtration of the water column by benthic fauna, and a tidal energy subsidy that leads to a highly productive benthos whose production is directly linked to rates of overlying primary production (Nixon 1988; Hermann et al. 1999).

Primary production in coastal lagoons, bar-built estuaries, fringing regions of deeper estuaries, and other similar shallow systems is often enhanced by light penetration to the bottom. This light supports a diverse array of benthic primary producers including microalgae (diatoms and cyanobacteria—often termed "benthic microalgae" or "microphytobenthos"), macroalgae, and seagrasses (Fig. 1). We define these types of waterbodies as "shallow coastal photic systems." The presence of multiple primary producers in shallow systems may ensure maximum use of light energy in all seasons (Schelske and Odum 1962). These benthic producers often have areal rates of production far exceeding those of phytoplankton (see compilation by Valiela 1995). The diversity of primary producers combined with enhanced benthic–pelagic coupling in these shallow, well-mixed systems contributes to high rates of secondary production and fishery yields in the same range as those for deeper estuaries (Nixon 1982, 1988, 1992; Nixon et al. 1986). The vegetated shallows of these systems provide important nursery habitat and refuge for fish and shellfish with elevated rates of secondary production relative to nonvegetated regions (Orth et al. 1984; Heck et al. 1995, 2003).

An additional source of primary production found along the perimeter of both deep and shallow coastal systems is provided by salt and freshwater tidal marshes (Fig. 1). These marshes are often a more dominant feature of shallow systems, as evidenced by greater ratios of marsh to open water area in lagoons and shallow embayments relative to deeper estuaries (Nixon 1980). Additionally, in deeper systems, marshes are connected to open water areas through shallow, nearshore zones. This review focuses on subtidal ecosystems and therefore considers emergent marshes to be at the landward boundary of shallow coastal photic systems; nevertheless, these marshes perform a number of important ecosystem functions that affect the adjacent subtidal systems and can serve to buffer the response of shallow coastal photic systems to natural and anthropogenic stressors. Exchanges of materials between marshes and adjacent open waters have long been a topic of intense interest in marine ecology, with some marshes providing important energy and detrital subsidies to subtidal food webs and performing a number of nutrient transformations (Teal 1962; Odum 1968, 2002; Nixon 1980; Anderson et al. 1997; Neubauer et al. 2000, 2005; Childers et al. 2002). Additional functions of emergent marshes that impact adjacent coastal systems include buffering of wave energy, shoreline stabilization, water storage during storms, provision of nursery habitat and predation refuge, enhanced removal of sediments via settling, and enhanced removal of nutrients through denitrification and phosphorus burial (Peterson et al. 2008; Jickells and Weston 2011; Vieillard and Fulweiler 2012; Barendregt and Swarth 2013; Ensign et al. 2013).

Shallow photic systems play a critical role in processing land-derived nutrients on their transit from watersheds to the coastal ocean, as nutrients can be sequestered by benthic micro- and macroalgae or removed by denitrification (Fig. 1) (Anderson et al. 2003, 2010; Sundbäck et al. 2004; McGlathery et al. 2007). The action of this "benthic filter" can mediate against the effects of anthropogenic nutrient loading, which often arrives via groundwater as base flow as well as the riverine inputs typical in deeper systems (Stanhope et al. 2009). This filter combined with rapid nutrient uptake by seagrasses and epiphytes leads to a major difference in the response of shallow systems to nutrient enrichment relative to their deeper counterparts (Fig. 2a). Mesocosm experiments showed that water column concentrations of dissolved inorganic nitrogen (DIN) increased monotonically with increasing loads in relatively deep, plankton-based mesocosms designed to represent Narragansett Bay (Nixon et al. 2001). In contrast, DIN concentrations remained extremely low and were unresponsive to loading in shallow, photic, seagrass mesocosms designed to represent the lagoons of the Rhode Island coastline.

Shallow coastal photic systems receive additional inputs of fixed nitrogen via sediment and epiphytic nitrogen fixation (Eyre et al. 2011; Howarth et al. 2013; Anderson et al. 2014; Hayn et al. 2014). Given their proximity to land-based nutrient loads, shallow depths, small volumes, and relatively long water residence times, shallow coastal photic systems are vulnerable to rapid changes in population, land use, and associated nutrient loads, along with potential changes in water temperature, sea level, and freshwater delivery related to climate change (Kennish and Paerl 2010a, b; Najjar et al. 2010). Despite relatively smaller ratios of watershed to open water area, lagoons and similar systems are characterized by the same range in nutrient loading as deeper, plankton-based estuaries (Nixon et al. 2001; McGlathery et al. 2007; Moore et al. 2012).

While the response of relatively deep, plankton-based estuaries to increasing nitrogen loads has been related predictably to phytoplankton biomass as chlorophyll-*a* or primary production (Nixon 1992; Nixon et al. 1996; Boynton and Kemp 2000), these relationships have been less evident in shallow systems (Fig. 2b, c) (Borum and Sand-Jensen 1996; Nixon et al. 2001; Giordano et al. 2011). Notable exceptions are the strong positive relationships between nitrogen loads and concentrations of total nitrogen and chlorophyll-*a* in the Maryland Coastal Bays (Boynton et al. 1996). More commonly, lagoonal systems exhibit a shift from subtidal autotrophic dominance by submerged aquatic vegetation (SAV) to nuisance blooms of phytoplankton and macroalgae as eutrophication progresses. Such observations in a limited number of systems have led to a prevailing conceptual model of a transition from SAV to macroalgae to phytoplankton as nutrient loads increase (Duarte 1995; Valiela et al. 1997; Havens et al. 2001; Nixon 2009), although these models exclude the role played by benthic microalgae.

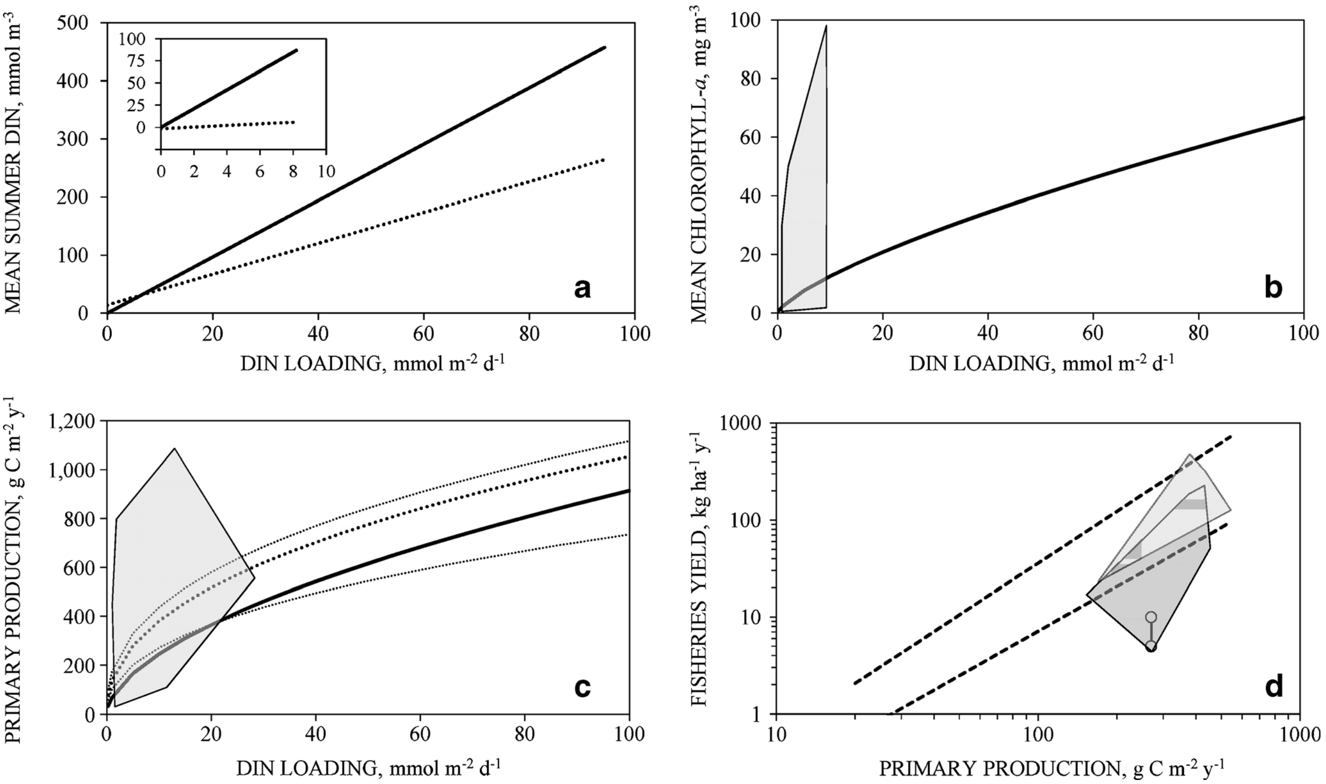

Fig. 2 **a**–**c** Differential responses of deep and shallow coastal systems to nutrient loading, redrawn from Nixon et al. (2001). **a** Main panel: relationship between dissolved inorganic nitrogen (DIN) loading and mean summer DIN concentrations in the 5-m deep, plankton-based Marine Ecosystems Research Laboratory (MERL) nutrient gradient experiment. *Solid line* is the steady-state concentration due solely to loading and flushing; *dashed line* is the regression to the data. *Inset*: same but for the 1.1-m deep, seagrass mesocosms at the University of Rhode Island. Tanks were not loaded across the same range as in the MERL experiment. **b** Regression between mean annual chlorophyll-*a* concentrations and loading in the MERL experiment. *Shaded region* shows the range of mean summer chlorophyll-*a* concentrations observed in the shallow, seagrass mesocosms. **c** As for **b**, but for annual primary production in the MERL tanks (*bold line*) and the synthesis of rates from shallow systems of Nixon et al. (2001) (*shaded region*). *Dashed* and *dotted lines* give the regression and upper/lower envelopes, respectively, of the data compiled primarily from deeper estuaries by Nixon et al. (1996) for comparison. **d** Relationship between annual primary production and fisheries yield based on Nixon (1982, 1988, 1992) and Nixon et al. (1986). *Dashed lines* show the upper and lower envelopes of the data from all marine ecosystems, excluding the *open circles* which fell outside this envelope. *Dark-shaded region* encompasses the points from relatively deep estuaries, while the *light-shaded region* encompasses the points from lagoonal and other shallow photic systems

However, in a cross-system comparison of very shallow marine ecosystems, a clear shift in the dominant autotroph with increasing nitrogen loading was not demonstrated (Nixon et al. 2001). While macroalgae were more prevalent at higher nitrogen loads and eelgrass at lower loads, there were exceptions to this pattern, and phytoplankton-based systems occurred across the full range of loading. Curiously, regressions of primary production and fisheries yield do not indicate differences in the yield between deep estuaries and shallow lagoons (Nixon 1982, 1988, 1992; Nixon et al. 1986) (Fig. 2d).

Many reasons can account for the complicated responses between loading and chlorophyll-*a* or primary production demonstrated in shallow systems. A variety of features act as "filters" that modulate the response to nutrient loads, including tidal energy, residence time and currents, optical properties, and presence of suspension feeders (Cloern 2001). Indeed, water residence time can play a major role in determining the succession of dominant autotrophs with increasing nutrient loading (Valiela et al. 1997). The ongoing "natural experiment" of global climate change is creating further filters that modulate shallow photic ecosystem response due to changes in sea level, water temperature, freshwater delivery, and storm activity (Najjar et al. 2010). The combined effect of multiple stressors and internal filters may result in nonlinear recovery trajectories and changes in stable states within these systems (Scheffer et al. 2001; Viaroli et al. 2008; Duarte et al. 2009).

The difficulty in developing widely applicable conceptual models of shallow system response to nutrient loading has fueled a common notion that our understanding of shallow photic systems has lagged behind that of deeper estuaries. In this paper, we review the natural and anthropogenic drivers of change in shallow coastal photic systems in an attempt to illustrate the wide range of stressors and processes at work in these systems. We then introduce the papers included in this special issue which illustrate a number of the concepts discussed below.

Drivers of System Change

Natural Forcing Factors/Disturbances

This special issue provides detailed descriptions of the physicochemical and biotic characteristics, habitat conditions, and the natural and anthropogenic drivers and stressors of change encountered in shallow coastal photic systems that affect their hydrologic, biogeochemical, and trophic properties and modulate their responses (i.e., "filters"). It also examines the tools and approaches (i.e., indicators, trend analysis, multivariate analytics, modeling) used to assess ecological structural and functional changes and touches on the science-based management efforts necessary to deal with both the anthropogenic and naturally induced changes. To guide the discussion, we offer a conceptual model based on Cloern's (2001) phase III model of coastal eutrophication (Fig. 3).

Shallow coastal photic systems are particularly susceptible to the flux of physicochemical factors, which typically affect the entire water column of these systems and the coupling of benthic and pelagic regimes (Kennish and Paerl 2010a). Temperature, light, and nutrients are key parameters regulating system production. Aside from light and temperature, physical factors such as water column depth, stratification, tidal energy, horizontal transport, wind-driven resuspension, and sediment composition influence benthic and pelagic processes greatly (Anderson et al. 2010).

Variations in precipitation and evaporation, surface water runoff, and groundwater discharges, together with wind forcing and density gradients, account for large advective transport fluxes in these shallow coastal photic systems. Suspended sediments, together with algal blooms generated by nutrient enrichment from coastal watersheds, result in high turbidity, increased light attenuation in the water column, and changes in both the quantity and quality of irradiance reaching the bottom (Cerco and Moore 2001). Light attenuation contributes to observed seagrass declines in shallow estuarine waters (Duarte 1991; Larkum et al. 2006; Moore and Jarvis 2008; Fertig et al. 2013). These factors can reduce primary production significantly and cause shifts in the composition of phytoplankton and benthic primary producers, including microalgae, macroalgae, and macrophyte assemblages that modulate higher trophic level dynamics. In contrast, nutrient enrichment usually increases system production and the genesis of eutrophic conditions (McGlathery et al. 2007; Anderson et al. 2010).

Catastrophic, episodic natural events—notably major hurricanes, tropical storms, and northeasters—inject large pulses of freshwater into estuaries, restructure barriers enclosing shallow lagoons, and alter other properties of receiving waters. Storm and wind surges; overwash events; inlet reconfigurations; land reclamation; construction of dams, dikes, and artificial bars; as well as channel dredging events are also important drivers of hydrological change. Sudden increase in hurricanes and tropical storms since the mid-

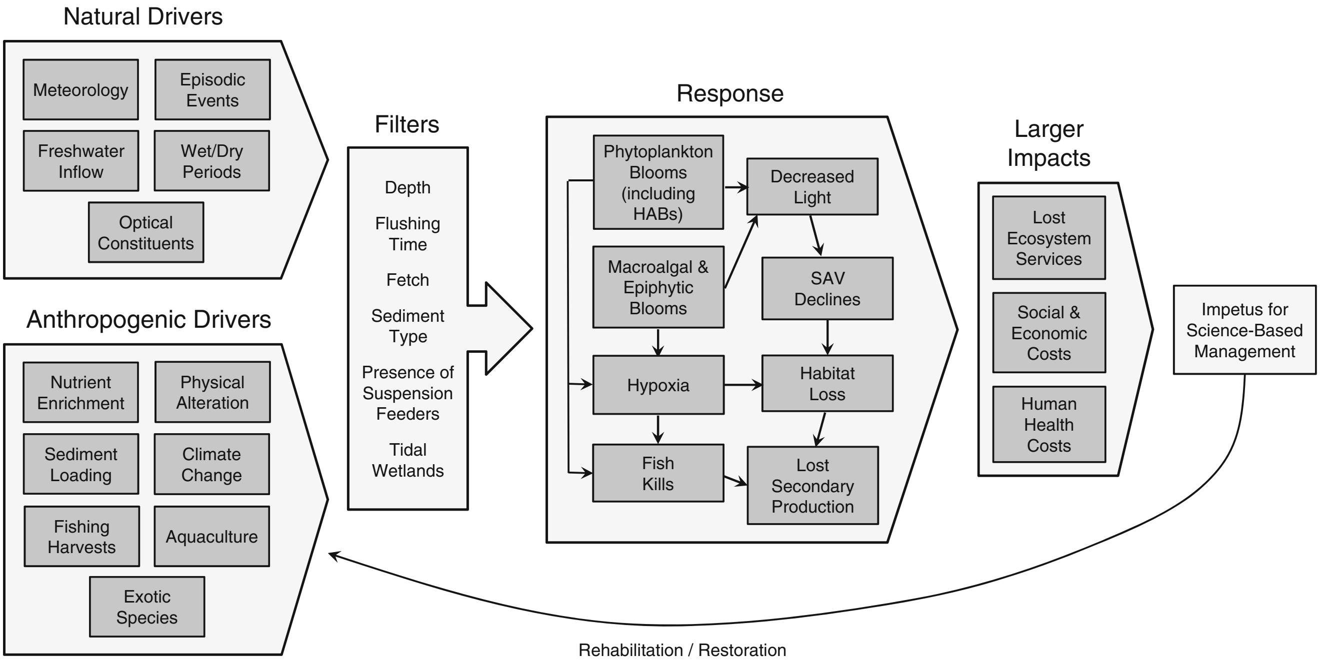

Fig. 3 Conceptual model of drivers, filters, responses, and larger impacts in shallow coastal photic systems, following the Phase III conceptual eutrophication model of Cloern (2001)

1990s in the mid-Atlantic and Gulf Coast regions of the USA that have significantly affected hydrologic processes, albeit ephemerally, and the physicochemical characteristics of estuarine and shallow coastal marine environments (Paerl et al. 2009, 2010) can cause marked shifts in salinity structure and flushing times, nutrient concentrations, and total suspended solids. These changes can also significantly alter ecosystem functions, such as denitrification and nitrogen fixation.

Some shallow coastal photic systems, including many lagoons in southern California, have seasonal river inflow (Kennison and Fong 2014). Others experience periodic closure of sand bars and thus experience wide variation in salinity from nearly freshwater to hypersaline. These systems are subject to dry and wet seasons with wide ranges of meteorological forcing factors that can affect water quality and biotic communities (Zedler 2001). Seasonal and interannual climatic-driven ecological change has also been documented in shallow coastal photic systems along the Atlantic and Gulf coasts of the USA (Kennish and Paerl 2010b; Paerl et al. 2010).

Nutrients accumulate in pore waters of bottom sediments via microbial decomposition of decaying plant matter, and this process often creates hypoxic conditions and sulfide generation that is toxic to benthic organisms and regulates the cycling of carbon and nitrogen. Microbial mediated processes in bottom sediments (nitrogen fixation, nitrogen remineralization, nitrification, denitrification, anammox, and dissimilatory nitrate reduction to ammonium) can determine nitrogen availability for primary production in benthic and pelagic habitats and are important in regulating the relative magnitude of benthic versus pelagic primary production (Anderson et al. 2010). Nitrogen concentrations in bottom sediments of coastal bays are typically much higher than those in the water column. Microbially mediated regeneration of nitrogen, remobilization of nitrogen in bottom sediments, and subsequent resuspension of pore waters support algal growth in the water column and can stimulate bloom development (Burkholder et al. 2007; McGlathery et al. 2007).

There is characteristically a strong benthic–pelagic coupling in shallow coastal photic systems, and the benthos plays a key role in mediating nutrient cycling processes (Valiela et al. 1997; McGlathery 2001; McGlathery et al. 2007). Nitrogen fixation and nitrogen remineralization, which occur primarily in bottom sediments of shallow coastal photic systems, account for much of the nitrogen generated autochthonously that supports production of benthic microalgae, macroalgae, and seagrasses (Anderson et al. 2003; Tyler et al. 2003; Fulweiler et al. 2007; Fulweiler and Nixon 2009). Benthic microalgae assimilate nitrogen released from sediment pore waters, thereby reducing the potential for eutrophication, which commonly occurs in coastal lagoons and other shallow coastal bays with high secondary nutrient inputs from the benthos and elevated water residence times (Kennish and de Jonge 2011).

Sufficient light availability is necessary to maintain healthy dominance of benthic flora in shallow coastal photic systems. Indeed, Burkholder (2001) found that light reduction had a greater negative effect on seagrass shoot production than did increased nitrogen availability. The minimum light requirements of seagrasses generally vary between 5 and 20 % of surface irradiance (Dennison et al. 1993). Hence, light attenuation in the water column due to suspended particulates, dissolved substances, and epiphytes on photosynthetic surfaces of the plants often harms seagrass beds. These factors cause depth limitation of seagrass (Duarte 1991). Nutrient over-enrichment promotes nuisance and toxic algal blooms (phytoplankton and macroalgae), as well as epiphytic growth on eelgrass blades which reduce light availability (up to 90 %) for eelgrass function (Brush and Nixon 2002; McGlathery et al. 2007; Paerl et al. 2003, 2009). Light reductions are linked to lower eelgrass shoot densities, slower growth rates, stunted morphology, and higher mortalities (Ochieng et al. 2010).

Wind- and current-driven resuspension of sediments may be more important than phytoplankton abundance in attenuating light in the water column of shallow coastal photic systems (Cerco and Moore 2001). In contrast, phytoplankton may be the primary factor limiting light penetration in deeper estuarine systems (Lawson et al. 2007; Anderson et al. 2010). Diminished light transmission to the estuarine floor leads to the replacement of seagrass by opportunistic macroalgae (e.g., *Ulva* and *Enteromorpha*), filamentous epiphytic macroalgae, and phytoplankton that require lower light intensities for survival (Brush and Nixon 2002; Hily et al. 2004; McGlathery et al. 2007; Kennish et al. 2011). An increase in algal epiphytes accelerates seagrass decline (Heck and Valentine 2007). The resulting shift in bottom-up controls often resonates through upper trophic levels. The loss of seagrass habitat due to light attenuation affects trophic structure by reducing the abundance of herbivorous grazers which can control algal overgrowth and serve as a food source for higher organisms (Burkholder et al. 2007). Degraded eelgrass areal cover may also eliminate habitat for bay scallops (*Argopecten irradians*), hard clams (*Mercenaria mercenaria*), and other benthic and nektonic resource species, and cause changes in ecosystem structure and function driven by bottom-up effects (Kennish et al. 2010; Kennish and de Jonge 2011).

Short-term, acute meteorological perturbations including heat waves, droughts, and floods cause extreme fluxes in hydrodynamics and biotic responses in shallow coastal photic systems. Along with longer term stressors, they also influence ecosystem stability and resilience (Elliott et al. 2007). Such variability differentially affects physicochemical properties (salinity, residence time, transparency, stratification, and hypoxia) and with subsequent effects on primary production and community respiration. Both hydrology and wind forcing are important drivers of change and must be clearly integrated with nutrient, sediment, and other pollutant loadings when assessing and managing short- and long-term ecological impacts on these systems. Analysis of biotic responses to freshwater pulses, nutrient enrichment, elevated turbidity, and other drivers of change often involves biotic indicators and bioassessment protocols (Paerl et al. 2007; Fertig et al. 2014).

Climate change and associated sea-level rise are having an increasing effect on shallow coastal photic systems and must be factored into management strategies for water quality improvement and ecosystem sustainability. Global sea level may rise 80 cm by 2100 (Miller et al. 2009). Climate forecasting models indicate an increasing frequency and severity of damaging storms, storm surges, and flooding of coastal environments as global temperatures increase during the twenty-first century (Labat et al. 2004; IPCC 2007). In addition to sea-level rise threatening the shoreline, storm surges will impact the coastal zone far inland and threaten coastal communities via inundation, as occurred along the New Jersey coast during "superstorm" Sandy in October 2012. These drivers of change will have increasing impacts on the abiotic and biotic characteristics of shallow coastal photic systems. Rising sea level will displace ocean and bay shorelines landward, threaten salt marsh sustainability, and alter estuarine salinities and temperature, water depth, tidal prisms, circulation, residence times, and biotic communities. Loss of wetlands habitat as the sea encroaches, particularly in areas where wetlands migration is obstructed by human structures, will impact finfish and wildlife populations dependent on this habitat for survival. Stocks of finfish and shellfish species will decline from ocean transgression (Kennish et al. 2008b).

Anthropogenic Forcing Factors/Disturbances

Shallow coastal photic systems rank among the most heavily impacted aquatic ecosystems, being affected by a wide range of anthropogenic activities both in adjoining coastal watersheds and in the waterbodies themselves (Kennish 2002; Kennish and Paerl 2010b). Shallow coastal bays are especially susceptible to anthropogenic stressors and drivers of change linked to rapid population growth and development of the coastal zone. They typically have a large surface area to volume ratio and are responsive to nutrient enrichment. Semi-enclosed coastal lagoons, bounded by barrier island complexes, reefs, and sand bars, with protracted water residence times and limited flushing, are vulnerable to nutrient enrichment because bloom-forming algal populations have time to assimilate nutrients and grow. Nutrient enrichment stimulates algal blooms that lead to large accumulations of organic matter in bottom sediments that serve as a secondary source of nutrients for recycling to the water column.

While anthropogenic stressors have received the greatest attention in eutrophied coastal lagoons and bays, natural stochastic events (e.g., major storms, storm surges, upwelling, severe winds, and coastal flooding) interacting with these stressors exacerbate the environmental effects. However, such natural events occur episodically relative to some anthropogenic stressors (Paerl et al. 2006). In addition, multiple anthropogenic disturbances create both acute and insidious problems for many estuarine biotic communities and habitats that can compromise the stability and resiliency of these systems and their long-term integrity. Management of these systems to remediate impacts is complicated by the growing body of evidence indicating that restoration does not follow the same trajectory along which the systems declined (Duarte et al. 2009).

The list of anthropogenic impacts on shallow coastal photic systems is extensive and can be divided into physical, chemical, and biotic stressors. The major anthropogenic stressors include eutrophication, habitat loss and alteration, shoreline development, sewage wastes, chemical contaminants, human-induced sediment/particulate inputs, overfishing, introduced/invasive species, intensive aquaculture, human-altered hydrological regimes (e.g., freshwater diversions), climate change, land subsidence due to water and gas extraction, and floatables/debris (Table 1). These factors affect the ecological integrity, long-term viability, and human use of estuarine systems.

Anthropogenic stressors of shallow coastal photic systems may be categorized by whether they compromise water quality, alter biotic communities, or degrade habitat. Stressors that impact water quality include (chemical) pollution due to nutrient enrichment, organic carbon loading, and chemical contaminants. Stressors that alter biotic communities include pathogens, overfishing, and introduced/invasive species. Primarily, physical stressors degrade habitats and include dredging and ditching, shoreline modification, and wetland reclamation; however, chemical pollution can also destroy essential habitat such as seagrass beds (Moore and Wetzel 2000; Orth et al. 2006; Kennish et al. 2008a, 2010; Kennish and de Jonge 2011).

Environmental impacts on coastal bays, lagoons, and shallow coastal marine embayments escalate as population growth and development increase in adjacent watersheds. The conversion of forest and other natural vegetative cover to urban, suburban, and agricultural land cover has been linked to accelerated delivery of nutrients and other pollutants from point and nonpoint sources (Kennish 1997; McGlathery et al. 2007; Anderson et al. 2010). Nutrient loading from nonpoint sources (surface water runoff, groundwater discharges, and atmospheric deposition) and point sources (sewage treatment plants, pulp mills, and animal feedlots) is assimilated rapidly by algae in shallow coastal waterbodies, promoting phytoplankton and macroalgal blooms detrimental to seagrass beds and associated benthic invertebrate communities (Kennish et al. 2008a, 2010; Kennish and de Jonge 2011; Fertig et al. 2013).

Table 1 Major anthropogenic stressors on estuarine ecosystems

Stressor	Impacts
1. Eutrophication	Degraded water quality, biogeochemical alteration, loss of essential habitat (e.g., seagrass and shellfish beds), declining harvestable fisheries, imbalanced food webs, decreasing system resilience, diminished ecosystem services
2. Habitat loss and alteration, shoreline hardening and erosion	Usable habitat eliminated for estuarine biota
3. Sewage and organic wastes	Increased nutrient and organic carbon loading, pathogen inputs, degraded water and sediment quality, eutrophication, hypoxia and anoxia, reduced biodiversity
4. Chemical contaminants	Ecotoxicological impacts, degraded water and sediment quality, reduced population and community abundance, organism physiological and behavioral abnormalities, organ and system dysfunction, tissue degeneration, genetic derangement
5. Human-induced sediment/particulate inputs	Altered water and sediment quality, light attenuation, shading impacts, habitat modification, reduced primary production
6. Overfishing	Finfish and shellfish depleted stocks, altered food web structure
7. Intensive aquaculture	Habitat conversion, changes in hydrological regimes, degradation of water and sediment quality
8. Introduced/invasive species	Changes in species composition and distribution, altered trophic structure and organism abundance, reduced biodiversity, introduction of pathogens
9. Human-altered hydrological regimes	Modified salinity (which regulates microbial processing of nitrogen), temperature, and habitat; altered species composition and abundance
10. Climate change	Sea-level rise, wetlands habitat loss, altered temperature and salinity regimes, changes in biotic community structure and ecosystem function
11. Subsidence due to water and gas extraction	Accelerated fringe/edge effects, altered wetlands, expansion of open water habitat, impacted biotic communities
12. Floatables/debris	Damaged habitats, loss of higher trophic level organisms (i.e., seabirds, marine mammals, reptiles, and other animals)

Land-use change due to urbanization/suburbanization of upland watersheds and shoreline areas is a major stressor. Animal feedlots and agricultural operations augment these effects. The amount of impervious cover increases with urbanization of watershed areas (building construction, roadways, bridges, etc.). A watershed impact threshold of degraded water quality is exceeded when the amount of impervious surface cover surpasses 10 % (Arnold and Gibbons 1996). Impervious cover, compacted soils, and other altered watershed surfaces serve as a conduit to transport pollutants in stormwater discharges and general surface runoff to area waterways. Pollutant delivery problems are magnified where storm sewers are subject to combined sanitary and storm sewer overflows.

Infiltration of precipitation decreases while runoff volume increases with increased removal of forest land cover and other natural vegetation. Surface runoff is facilitated by aging infrastructure and poorly maintained stormwater systems which deliver chemical pollutants and sediments to receiving waters and cause erosion problems. Resolution includes upgrading watershed management plans to incorporate sound land use and site planning to control water pollution and revising master plans and zoning ordinances. In addition, the best management practices are vital, such as reducing fertilizer, herbicide, and pesticide use; replacing lawns with natural vegetation (ground covers, trees, and shrubs); modifying agricultural practices; constructing stormwater basins and sediment traps; creating wetlands, rain forests, and other filtering habitat; and instituting alternative landscaping designs and street sweeping. Engineering controls of nonpoint source pollution to protect area waterways are costly, but should be implemented concomitantly with watershed development to help control watershed and waterway impacts.

Shoreline development causes considerable habitat loss and alteration of biotic communities. Extensive shoreline areas of shallow coastal bays and the nearshore ocean are lined with bulkheads, revetments, retaining walls, and other shore-protection features. Docks, piers, boat ramps, and marinas are common in back-bay systems. These structural features disturb natural landscapes, alter physical (e.g., wave and current activity) and chemical processes, and elicit an array of biotic responses (e.g., settlement and proliferation of epibenthic communities) (Dugan et al. 2011). For example, bulkheads and other shoreline armoring may reduce erosion of developed shorelines to steepen shorelines, deepen bayside bathymetry due to increased current activity and sediment erosion, and eliminate intertidal and shallow subtidal estuarine habitats (Nordstrom 2000). In addition, anthropogenic changes can degrade adjacent nearshore zones (Seitz et al. 2006). Dredging for lagoon construction, harbor development, and channel enlargement alters flushing and circulation patterns. Recreational and commercial fishing activities, aquaculture and mariculture operations, and shoreline stabilization and hardening can significantly impact water quality and biotic community structure. Considerable nursery, reproductive, and refuge habitat can be impacted by these activities as well (Zaikowski et al. 2008). The loss of estuarine beach, marsh, and other wetland habitat in developed areas leads to a reduction of water filtration and the loss of essential ecosystem functions (Bilkovic et al. 2006; Bilkovic and Roggero 2008).

As land alteration and impervious cover increase, open space declines and surface runoff of pollutants from coastal land surfaces rises dramatically. Increased nutrient loading will lead to cascading adverse effects on biotic communities and habitats in receiving waters (Kennish and de Jonge 2011). Septic system leakage, wastewater from treatment plants, animal feedlot wastes, and symbiotic nitrogen fixation from leguminous crops augment these sources. Farmlands and urbanized watersheds are major allochthonous sources of nitrogen and phosphorus to estuarine and coastal systems.

Eutrophication has increased substantially in shallow coastal photic systems worldwide and has escalated rapidly as a primary stressor of many shallow coastal systems concomitantly with greater agriculture and domestic fertilizer use (Nixon 1995; Howarth et al. 2000a, b, 2002a, b; Cloern 2001; Nixon et al. 2001; Howarth and Marino 2006; Howarth 2008; Kennish 2009). Eutrophication has been defined as an increase in the rate of supply of organic matter to a system leading to degradation of ecosystem structure and function (Nixon 1995, 2009). Impacts of eutrophication are numerous and varied and, depending on physicochemical and biotic conditions, may include the occurrence of hypoxia/anoxia, harmful algal blooms (HABs), epiphytic growth, biogeochemical alteration, loss of essential habitat (e.g., seagrass and shellfish beds), reduced biodiversity, declining harvestable fisheries, imbalanced trophic food webs, decreasing system resilience, diminished ecosystem services, and impacted human use (Kennish et al. 2007). These eutrophic effects are documented in coastal lagoons and other shallow coastal photic systems worldwide (Kennish and Paerl 2010a).

Eutrophication disrupts the trophic dynamics and functioning of coastal waterbodies, most notably in coastal lagoons and other shallow coastal photic systems (Kennish et al. 2007; Kennish and de Jonge 2011). The resulting elevated phytoplankton and macroalgal biomass found in eutrophied systems promotes large fluxes of organic matter to the estuarine floor and their accumulation on the seabed, setting into motion bottom-up controls and the disruption of biotic and biogeochemical processes. Far greater concentrations of nitrogen are typically stored in bottom sediments of coastal lagoons (often 10- to 100-fold higher in bottom sediments than in the water column; Sand-Jensen and Borum 1991; Burkholder et al. 2007). Mesocosm experiments showed that up to half of the nitrogen stored in macroalgae tissue is transferred to sediments during microbial decomposition (Anderson et al. 2010). This nitrogen is then removed by nitrification/denitrification or available to flux into the water column and support additional primary production. The resulting phytoplankton blooms can be sustained for months to years in systems with protracted residence times (Glibert et al. 2010).

Nutrient enrichment and the large flux of organic matter to the estuarine floor favor deposit feeders over filter feeders in benthic communities. There is frequently a progressive change from larger, long-lived benthos (e.g., hard clams, *M. mercenaria*) to smaller, rapidly growing, but shorter lived forms (e.g., *Mulinia lateralis*). The loss of larger, filter-feeding shellfish species has been well documented in Barnegat Bay-Little Egg Harbor, New Jersey, a highly eutrophic coastal lagoon (Kennish et al. 2007). The loss of filter feeders reduces top-down control and regulation of phytoplankton blooms. With less top-down control, harmful algal blooms may occur more frequently (e.g., brown tide, *Aureococcus anophagefferens*). The potential for permanent alteration of biotic communities and habitats exists in impacted system, as their stability and resilience are altered. Species composition, abundance, distribution, and diversity of organisms vary considerably in eutrophied systems. Opportunists and nuisance organisms (e.g., macroalgae; *Enteromorpha*, *Gracilaria*, and *Ulva*) often dominate these systems, outcompeting and replacing more desirable and stable forms, such as seagrasses. Extensive phytoplankton and macroalgal blooms, epiphytic overgrowth on seagrass leaves, and suspended particulates also create unfavorable shading conditions for seagrass beds and cause dieback and elimination of this essential benthic habitat for crabs, fish, and benthic invertebrates (Kennish and Fertig 2012).

The accumulation of large amounts of decaying algae during bloom events promotes hypoxic conditions and production of sulfides in bottom sediments mediated by microbial decomposition (de Jonge et al. 2002; Rabalais 2002; Kennish and de Jonge 2011). Such events can be damaging to benthic communities and habitats. Acute hypoxic areas, often called dead zones, commonly develop during summer in the deeper waters of systems (such as Chesapeake Bay, northern Gulf of Mexico, and the Danish coast) corresponding to a period of thermally controlled stratification (Diaz and Rosenberg 1995; Rabalais 2002, 2005). Pycnocline development exacerbates oxygen depletion by precluding mixing of surface and bottom waters, with progressive depletion of oxygen in deeper waters. Benthic communities are particularly susceptible to this process, although nekton are also impacted. Dissolved oxygen (DO) levels below 3 mg L^{-1} generally result in adverse physiological and behavioral responses and increasing mortality in affected biota. At a DO concentration of 0 mg L^{-1}, anoxia culminates in massive mortalities and acute ecological effects on biotic communities and habitats. The number of hypoxic (DO<2.0 mg L^{-1}) regions in coastal waters worldwide increased by 33 % between 1995 and 2007 (Diaz and Rosenberg 2008), covering a period of time when eutrophic waters also increased dramatically (Kennish and de Jonge 2011).

Harmful algal blooms (HABs) have also escalated in coastal marine waters worldwide with greater incidence of nutrient enrichment (Anderson and Garrison 1997; Anderson et al. 2002; Livingston 2000, 2002, 2006; Paerl et al. 2008; Glibert et al. 2010). Of the total number of marine phytoplankton species (~5,000), only about 40–50 are classified as HABs that produce toxins affecting marine organisms and humans (Hallegreaff 1995). They have a devastating impact on commercial and recreational fisheries. Representative groups include diatoms, cyanobacteria, pyrmnesiophytes, dinoflagellates, and raphidophytes. A number of species are common in coastal bays and embayments, such as *A. anophagefferens*, *Dinophysis* spp., *Heterosigma akashiwo*, *Chattonella* sp., *Karlodinium veneficum* (=*K. micrum*), *Microcystis aeruginosa*, *Pfiesteria* sp., *Pseudo-nitzchia* spp., and *Prorocentrum minimum*. HABs often discolor the water yellow, green, brown, orange, or red, and they cause shellfish poisoning, fish kills, and a range of other maladies. Red tide blooms have been particularly toxic to marine life (Hallegreaff 1995; Livingston 2002).

Restoration

Elliott et al. (2007) defined restoration as "the process of re-establishing, following degradation by human activities, a sustainable habitat or ecosystem with a natural (healthy) structure and functioning." The goal is to return an impacted system to a more improved pre-existing condition or state. Although the process of unmanaged restoration of shallow estuarine systems is common, human-mediated actions are typically employed such that estuarine habitat losses due to human activities or extreme natural events can be mitigated. Recovery of an impacted system from anthropogenic stressors may take up to 10–25 years after the stressors are removed, and an ecosystem may not be considered recovered unless secondary succession returns it to a pre-existing condition or state (Borja et al. 2010). However, recovery to the original natural state of a system is rarely achieved, as evidenced by the altered trajectories and multiple shifting baselines (Livingston 2006). For example, recovery of eutrophied estuaries from nutrient impacts has followed convoluted trajectories (Duarte et al. 2009). Three pathways may define the recovery process in an estuary which are as follows: (1) natural restoration through ecological restoration; (2) redirection through ecological restoration; and (3) unattainable recovery (Borja et al. 2010). One difficulty has been identifying unequivocally the reference status to which a damaged system is supposed to return after removal of a stressor.

Restoration is often implemented to overcome changes in the following elements of an ecosystem: (1) habitat fragmentation; (2) habitat and species diversity; (3) population size, dynamics, and range of species; and (4) goods and services (Madgwick and Jones 2002; Elliott et al. 2007). Estuarine restoration typically involves labor-intensive projects designed to improve water quality of land runoff, re-establish freshwater inflow, revegetate habitats (e.g., salt marsh, mangrove, and seagrass systems), repopulate shellfish beds, remove contaminated bottom sediments and hardened shoreline structures, install oyster reef substrate and living shorelines, and improve other structural and functional elements of the ecosystem. Restoration efforts targeting sheltered and fringing habitats such as salt marshes, mangroves, seagrasses, and biogenic reefs have been most successful (Alongi 1998; Orth et al. 2006, 2010; Elliott et al. 2007). Climate change, rising sea level, land subsidence, and extreme weather events are creating an even greater need for restoration efforts today, particularly in shallow coastal photic systems.

Restoration will play an increasingly important role in estuarine sustainability as ecological function of these vital shallow coastal systems is compromised by accelerating population growth and development pressures that degrade water quality, alter watershed and estuarine habitat, and deplete biotic communities (Lotze et al. 2006). Historically, restoration of the ecological structure and function of damaged systems has been more successful in shallow coastal bays, lagoons, and fringing habitats than in deeper estuaries (Elliott et al. 2007). In addition, ecological improvement has been demonstrated on smaller spatial scales (e.g., tens or hundreds of meters of estuarine floor or shoreline) than over the entire estuary. For those estuaries adversely affected by ecosystem-wide drivers of change, such as eutrophication, successful recovery will be more tenuous. Furthermore, natural extreme disturbances (e.g., hurricanes, earthquakes, and tsunamis) will change recovery trajectories by restructuring affected systems and altering restoration components and shifting restoration endpoints.

Future ecological restoration of shallow coastal systems will need to consider even further the rapidly changing baseline conditions influenced by not only anthropogenic effects of coastal population growth and development, but the ever changing environment. These changing baselines will have profound effects on the likelihood of success of restoration efforts. Choi (2004) suggests that there should be a shift in the restoration paradigm from "historic" to "futuristic" where dynamic goals are set for the future, rather than the past; where multiple trajectories are acknowledged and considered; and where ecosystem or landscape approaches are taken as much as possible. The dynamic nature of coastal systems and the challenges of managing and restoring these areas are highlighted in Burkett and Davidson (2012), where the complex stressor interactions, nonlinear system changes, and sudden shifts in state or "tipping points" of coastal ecosystems are becoming increasingly recognized. Continued emphases on new tools and new information such as provided in this special issue are needed to support and expand sustainable coastal management. Ecosystem-based modeling approaches at various system level scales (Tett et al. 2011) are central to refining our understanding of this complex system behavior. Restoration of important habitats, such as emergent wetlands and submersed aquatic vegetation and the ecological systems they support, is critical for improving ecosystem stability and resilience. Renewed emphasis and focus on an interconnection of research, monitoring, and modeling of shallow coastal photic systems will be required to set and meet goals as increasing socio-economic and natural stressors affect their stability and recovery under evolving future conditions (Duarte et al. 2009; Kirwan and Megonigal 2013).

Volume Plan

This special issue focuses on a myriad of natural and anthropogenic stressors that effect change in shallow coastal photic systems. It is the outcome of a session (*Drivers of change in shallow coastal photic systems*) at the 21st Biennial Conference of CERF held at Daytona Beach, Florida on November 7, 2011, which covered the physical, chemical, and biological drivers that regulate ecosystem dynamics in coastal systems where light reaches the benthos. Although the effects of natural (physical and climate) and anthropogenic (nutrient) stressors interact in their negative effects on shallow photic systems, the studies here are organized with those focused on physical drivers first, followed by those that highlight nutrient and other anthropogenic drivers of change. Restoration of the dominant primary producers to more stable states in these shallow water area is discussed throughout as are the implications of "tipping points" and other conditions leading to state change that are important for the development of effective management strategies. Overall, these papers demonstrate the vulnerability of shallow coastal photic systems to a multitude of stressors over both the short and long term. Changing climate may impact recovery even if the effects of controllable stressors can be reduced; however, these systems are resilient, and as demonstrated here, recovery and restoration may be possible.

Moore et al. (*Impacts of varying estuarine temperature and light conditions on Zostera marina* (*eelgrass*) *and its interactions with Ruppia maritima* (*widgeongrass*)) applied a temperature-dependent light model that relates eelgrass (*Zostera marina* L.) community compensating light requirements to light availability at three different sites located along a gradient of turbidity in the York River, Chesapeake Bay, Virginia. Eelgrass, a temperate seagrass species, is particularly sensitive to elevated temperatures near the southern limits of its range. In this study, regular measures of eelgrass abundance over an 8-year period were compared to the balance between compensating light requirements and light availability determined using in situ continuous measures of turbidity and temperature at each site. In the summer of 2005 and 2010, unusually high summertime water temperatures at the downstream study site in the York River for as short as 2 weeks corresponded to a significant dieback of eelgrass where beds had previously been persistent. In 2010, *Z. marina* lost an average of 97 % areal coverage from June to October in the lower river, and recovery was minimal. In contrast, *Ruppia maritima* increased in abundance. This downstream site, which had the greatest light availability, exhibited recovery during intervening years with more average summertime temperatures. The upstream study areas with higher turbidities and greater imbalances between light availability and light requirements showed greater negative effects with little recovery. An inverse relationship was also observed between monthly changes in eelgrass bed cover measurements and temperature with an inflection point between increases and decreases for the period of 2004–2011 observed at 23 °C. Increases in water temperatures combined with high levels of turbidity due to climate change or other factors, even for a short period during summer, pose serious long-term threats to eelgrass in this and other coastal systems.

Paerl et al. (*Hydrologic variability and its control of phytoplankton community structure and function in two shallow, coastal, lagoonal ecosystems: the Neuse and New River Estuaries, North Carolina, USA*) examined how hydrologic conditions can affect the phytoplankton community biomass and composition in microtidal, shallow estuarine systems. In this synthesis study, they investigated two systems in North Carolina, USA, using monitoring data collected from 1998 to 2011 for the Neuse and 2007 to 2011 for the New River. Here, they found that phytoplankton community composition and biomass were modulated strongly by the amounts, duration, and seasonality of freshwater discharges. In this region, as in others, there was an increase in frequency and intensity of extreme climatic events over the past 15 years, with each event exhibiting unique hydrologic and nutrient loading scenarios that had significant system-wide effects. The effects of these extreme events as well as more chronic seasonal changes in freshwater inputs exhibited distinctive unimodal relationships with flushing rates. These relationships can help predict relative changes in phytoplankton community composition. The predicted changes should be incorporated into water quality management strategies for these and other estuarine and coastal ecosystems faced with increasing frequency and variability in climatic events.

Anderson et al. (*Impacts of climate-related drivers on the benthic nutrient filter in a shallow photic estuary*) studied seasonally how the benthic filter, incorporating both microphytobenthos and denitrifiers, is important in reducing the release of remineralized NH_4^+ to the water column, thereby decreasing the potential for system eutrophication. Results for the New River Estuary, North Carolina, indicated that increases in temperature and freshwater delivery may initiate a cascade of responses affecting nitrogen cycling processes. Relationships observed between climatic drivers and system response suggest that increased effluxes of nitrogen to the water column may move shallow photic systems from net autotrophy toward net heterotrophy with new baselines characterized by degraded water quality.

Hayn et al. (*Exchange of nitrogen and phosphorus between a shallow lagoon and coastal waters*) documented the nutrient exchange between West Falmouth Harbor and Buzzards Bay, Massachusetts, during the 2005–2009 period when nitrogen loading increased substantially. A groundwater plume contaminated by a municipal wastewater treatment plant caused a 3-fold increase in nitrogen entering the harbor since 2000. Results indicate that the harbor retained the entire elevated watershed nitrogen load in summer and also had a net import of nitrogen from Buzzards Bay. However, the harbor was a net exporter of nitrogen to Buzzards Bay during the spring and fall. It retained about one half of the watershed nitrogen load over an annual period. In contrast, the harbor was a net importer of phosphorus in the spring and summer and a net exporter in the fall. Despite the large increases in nitrogen loading, this system illustrates how optically shallow systems dominated by benthic producers have the potential to retain large terrestrial nitrogen loads when there is a sufficient supply of phosphorus from exchange with coastal waters.

Christian and Allen (*Linking hydrogeomorphology and food webs in intertidal creeks*) provided an ecological network analysis of foodweb structure within the North Inlet estuarine system, South Carolina, examining the patterns and extent of tidal creek use by tidal migratory nekton. More specifically, they targeted two intertidal creeks in the North Inlet estuary to determine the relationship between foodweb structure and geomorphology and potential influences of hydrological condition and change. These intertidal creeks serve as both destinations and conduits for numerous predacious fishes and shrimps to access rich sources of prey. Most abundant nekton species feed largely on epibenthic or benthic invertebrates with high trophic efficiencies lower in the food chain. The conclusions indicate that shallow, wide intertidal creeks may have both physical and foodweb attributes that promote good nekton habitat relative to deeper and narrower creeks. In addition, human alterations to flow regimes and sea-level rise can affect geomorphology of individual creeks and in turn may alter food webs of the creeks and their ability to serve as food sources for the larger estuary.

Nidzieko et al. (*Contrasting seasonal and fortnightly variations in the circulation of a seasonally inverse estuary, Elkhorn Slough, California*) reported on community production, respiration, and advective oxygen exchanges in a shallow estuarine creek/marsh complex in Elkhorn Slough, California, and discussed the drivers of ecosystem metabolism in shallow estuaries where the tidal range is a significant fraction of the total depth. They utilized high-frequency biogeochemical and physical measurements to estimate the terms within a control volume budget for dissolved oxygen at tidal timescales during mid-summer. Measurements during impoundment of water at low tide were used to estimate the biological terms of the budget in the absence of tides. The authors noted large variations in net community production over the spring–neap tidal cycle, driven by the contribution from the intertidal marsh and the degree to which inundation occurred during day or night. Physical exchanges of oxygen from the creek to the marsh were balanced by advective fluxes up the creek from Elkhorn Slough. The approach presented by Nidzieko et al. should have wide-ranging applicability and provides a novel means of accounting for the effects of tides in studies of open water metabolism in meso- and macrotidal systems.

Boynton et al. (*Multi-decade responses of a tidal creek system to nutrient load reductions: Mattawoman Creek, Maryland USA*) investigated changes in key water quality (chlorophyll-*a*, nutrient concentrations, and water clarity) and habitat conditions (SAV communities) in Mattawoman Creek using time series data sets largely from 1986 to 2010. They tracked a major decrease of point source nutrient loads to Mattawoman Creek between 1991 and 1995 due to modification of a wastewater treatment plant. The annual average nitrogen loads were reduced from 30 to 12 g N m^{-2} $year^{-1}$ and phosphorus loads from 3.7 to 1.6 g P m^{-2} $year^{-1}$. In response to the large decline in nutrient loading, positive changes in water clarity, dissolved oxygen, algal biomass, and submerged aquatic vegetation areal cover were documented. This once highly eutrophic tributary creek now resembles the pre-1940's system condition.

Glibert et al. (*Eutrophication of a Maryland/Virginia coastal lagoon: a tipping point, ecosystem changes, and potential causes*) examined the decline of water quality in the Maryland/Virginia Coastal Bays linked to accelerated anthropogenic nutrient inputs. For example, total nitrogen concentrations are ~2-fold higher now than in the early 1990s, a trend associated with human activities. Biogeochemical processes have hastened water column accumulation of ammonium, and changes in the reducing nature of the system have developed with increasing nutrient loads. Phosphate concentrations have increased. Increased total nitrogen concentrations during this two-decade period have correlated with increased regional chlorophyll-*a* values and decreased submersed aquatic vegetation. Sustained summer picoplanktonic algal blooms (both brown tide and cyanobacteria), increased macroalgal blooms, and sporadic or sustained hypoxia now characterize the system. Declining ecosystem conditions are linked to a doubling of the human population in the coastal bays watershed since 1980.

Boneilla and Mulholland (*Interannual variability influences brown tide (Aureococcus anophagefferens) blooms in coastal embayments*) reported on the occurrences of

A. anophagefferens blooms in Chincoteague Bay, Maryland, between 2002 and 2007. Over this period, the intensity and duration of the blooms increased. Dissolved inorganic and organic nutrient concentrations, rates of nitrogen and carbon uptake, and the abundance of *A. anophagefferens* and co-occurring phytoplankton were compared over 6 years, five of which had significant bloom events. Results show that no single nitrogen compound was the driver for blooms; both inorganic nitrogen (e.g., ammonium and nitrate) and organic nitrogen (e.g., dissolved free amino acids and urea) were taken up during *A. anophagefferens* bloom events. In addition, both organic and inorganic carbon sources were assimilated by cells. Bicarbonate usually dominated carbon uptake during the daytime, but substantial organic carbon was taken up at night. Organic carbon uptake, which contributed up to 30 % of the total carbon uptake, increased as blooms progressed, likely due to light limitation from self-shading and/or depletion of dissolved inorganic carbon. Dissolved organic carbon also accumulated in the system.

Kennison and Fong (*Extreme eutrophication in shallow estuaries and lagoons of California is driven by a unique combination of local watershed modifications that trump variability associated with wet and dry seasons*) conducted a survey of five southern California estuaries ranging in size from 93 to 1,000 ha to determine if a relationship exists between nutrient concentrations (in the water column and bottom sediments) and the magnitude and seasonal distribution of macroalgal blooms. These estuaries are eutrophic largely due to nutrient enrichment from anthropogenic sources in coastal watersheds. Despite high system eutrophy, nitrogen availability in the water column and bottom sediments is not coupled to macroalgal biomass, possibly due to the saturation of biotic capacity to process nitrogen, disruption of natural hydrology, or nitrogen toxicity. Considerable variation in physicochemical and biotic conditions exists from one estuary to another, reflecting variable drivers of change in the adjacent watersheds.

Cebrian et al. (*Eutrophication-driven shifts in primary producers in shallow coastal systems: implications for system functional change*) addressed the patterns of shift in dominating populations of primary producers that occur in shallow coastal photic systems at incipient/moderate/intense levels of eutrophication. They also considered the interactive effects between water column oxygen content and functionality in these systems as eutrophication increases. Their study, which combines original research and literature data, suggests that blooms of macroalgae can have a positive effect on epifaunal abundance and secondary production under well-oxygenated conditions, but a negative effect if pervasive anoxic/hypoxic conditions develop with the bloom. Other factors, including water residence time and grazing rates, also affect eutrophication-driven shifts in primary producers at all intensities of eutrophication and must be understood to improve models of eutrophication as well as management efforts in shallow coastal systems.

Fertig et al. (*Mind the data gap: identifying and assessing drivers of changing eutrophication condition*) developed a new assessment tool, a Eutrophication Index, for Barnegat Bay-Little Egg Harbor, a highly eutrophic coastal lagoon along the central New Jersey coastline. Nitrogen enrichment is a major stressor that has led to altered biotic and habitat conditions. For example, multiple symptoms of eutrophication documented in this system include low DO concentrations, harmful and benthic algal blooms, heavy epiphytic loading, and declines in seagrass biomass. The Eutrophication Index developed for Barnegat Bay-Little Egg Harbor provides a holistic tool for assessing the ecosystem condition and identifying the drivers of these changes. The index is powerful in that it is capable of handling data gaps and identifying the conditions of and relationships between ecosystem pressures, ecosystem state, and biotic responses. The Eutrophication Index integrates 15 indicators in three components: (1) water quality, (2) light availability, and (3) seagrass response. Application of the Eutrophication Index over the 1989 to 2010 period reveals that the north segment of Barnegat Bay-Little Egg Harbor has been the most heavily impacted segment to nutrient loading, but the central and south segments are also undergoing eutrophication.

Caffrey et al. (*Seasonal and interannual patterns in primary production, respiration, and net ecosystem metabolism in three estuaries in the northeast Gulf of Mexico*) investigated seasonal and interannual variation in water quality and estuarine ecosystem metabolism using long-term monitoring databases collected at three estuarine sites of NOAA's National Estuarine Research Reserve System (NERRS) program. These systems include Grand Bay, MS; Weeks Bay, AL; and Apalachicola Bay, FL. Long-term trends in rates of gross primary production (GPP), ecosystem respiration (ER), and net ecosystem metabolism (NEM) were determined employing Odum's open water method. In all three estuaries, peak rates of GPP and ER exceeded 200 mmol O_2 m^{-2} day^{-1}. Long-term estimates of primary production and ecosystem respiration provide important fundamental information about the trophic status of estuarine environments.

Coda

We are pleased to present this special issue of *Estuaries and Coasts* and express our gratitude to the authors who submitted papers to this volume. Our goals both with the original session at CERF 2011 and in putting together this issue have been to produce a state-of-the-art overview of the myriad of natural and anthropogenic stressors that cause change in shallow coastal photic systems, the complex functioning of these systems, and the diverse suite of responses these systems exhibit to external stressors. We believe the papers in this volume accomplish that objective. Given that our understanding of shallow system function lags behind that for deeper estuaries, we feel such a compilation is timely and hope it serves to synthesize the present state of knowledge about shallow coastal photic systems.

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