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Introduction: Coastal Ecosystem Services at Risk

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ABSTRACT

Sustainable development depends on the provision of multiple marine ecosystem services. A comparative analysis of the northern Adriatic Sea and Chesapeake Bay conducted 20 years ago focused on ecosystem characterization and the impacts of local pressures (nutrient enrichment, fishing, and coastal development). To gain a better understanding of how these pressures are impacting sustainable development in the context of global climate change, an update of this analysis is presented in this book, with an emphasis on the pressures of nutrient enrichment and climate-driven changes in ocean temperature, acidification, and wet precipitation.

1.1. WHY COASTAL ECOSYSTEMS AND WHY THE NORTHERN ADRIATIC SEA AND CHESAPEAKE BAY?

Coastal ecosystems produce 80% of the world's annual marine fish catch (Pauly et al., 2008) and provide an estimated $12 trillion annually in coastal ecosystem services (Barbier et al., 2011; Costanza et al., 2017; Koch et al., 2009; Solé & Ariza, 2019; Worm et al., 2006) upon which sustainable development depends (Malone et al., 2014; UNEP, 2006; Wood et al., 2018). Four major categories of ecosystem services have been recognized (MEA, 2005):

1. Supporting services that underpin the capacity of coastal ecosystems, e.g., presence of critical habitats and biodiversity, primary production of organic nutrients and oxygen, and nutrient cycling. For our purposes, critical habitats include both pelagic habitats of the water column and biologically engineered benthic habitats (coral and oyster reefs, seagrass meadows, kelp forests, salt marshes and mangrove forests).
2. Regulating services, e.g., climate control, prevention of coastal erosion, limiting the extent and impacts of coastal flooding, and maintenance of water quality.
3. Provisioning services, e.g., supplies of food, raw materials, and medicinal resources.
4. Cultural services, e.g., recreational, aesthetic, and spiritual benefits.

Anthropogenic pressures that impact the capacity of marine ecosystems to provide services can be divided into two broad categories:

1. local pressures that are occurring globally (e.g., nutrient enrichment, fishing pressure, coastal development);
2. global, climate-driven pressures (e.g., ocean warming and acidification, sea-level rise, acceleration of the water cycle, the El Niño–Southern Oscillation) that have local consequences.

Together, local and global pressures interact to impact the capacity of marine ecosystems to provide services, especially in the coastal zone where these pressures converge and people and ecosystem services are concentrated (Elliff & Kikuchi, 2015; Solé & Ariza, 2019).

The rationale for comparing the two coastal systems of the northern Adriatic Sea (NAS) and Chesapeake Bay (CB) is that: both are well studied, semi-enclosed, river-dominated ecosystems subject to anthropogenic nutrient enrichment; both provide similar, economically important services that have been subjected to similar pressures during the course of the Anthropocene (Zalasiewicz et al., 2010); and together they offer contrasts in geomorphology and circulation that modulate their responses to anthropogenic pressures (Cloern, 2001).

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1.2. THE 1999 COMPARISON

Malone et al. (1999) published a comparative analysis of the NAS and CB. Here, we provide a brief description of the watersheds of the two systems and a synopsis of that comparison.

1.2.1. Overview of the Watersheds

Chesapeake Bay is a large estuary in the mid-Atlantic region of the United States with a watershed of 166,530 km^2 that hosts about 18 million people. Among its many tributaries, the Susquehanna River accounts for ~50% of total riverine inputs of freshwater into CB and its tributaries and discharges directly into the head of the bay's mainstem (Figure 1.1).

The watershed of the Susquehanna is dominated by forested areas (~65%). Agricultural and developed lands account for ~35% of the watershed but much higher proportions of nutrient inputs to CB. Major physiographical provinces in the CB watershed include Piedmont, Blue Ridge, Valley and Ridge, and Appalachian Plateau. Topographic conditions and soil permeability are variable within and among these regions. In general, steep slopes in the uplands of the Valley and Ridge contrast with gentle slopes of the Appalachian Plateau and Piedmont and flat terrain of the Coastal Plain. The ratio of watershed area to the volume of CB, an indicator of the extent to which land-use practices in the watershed can impact water quality in the bay, is 1400 km^{-1}.

The NAS is a semi-enclosed arm of the northeast Mediterranean Sea with sandy coasts and alluvial plains to the north and west and rugged mountains to the east. The watershed spans 110,600 km^2 and hosts about 20 million people. The Po River, the largest river discharging into the NAS, has a watershed that comprises 67% of the total NAS watershed and hosts large urban and industrial settlements, as well as extended areas of intensive cropping and livestock activities. Its watershed is bounded by two mountain ranges, the Apennines and Alps. In contrast to the CB, ~62% is in agriculture and developed land with only 34% forested (Malagó et al., 2019). However, with a watershed-area/seawater volume ratio of only 174 km^{-1} (compared to 1400 km^{-1} for CB), the potential impact of land-use practices on the NAS as a whole is much smaller than that for CB.

1.2.2. Nutrient Inputs, Circulation, and Nutrient Recycling

The Po and Susquehanna rivers are the primary sources of freshwater and anthropogenic nutrients to both systems and each accounts for about half of total riverine inputs of nitrogen and phosphorus. Thus, the distributions of salinity and nutrients within the NAS and mainstem of CB reflect inputs of freshwater and nutrients by the Po (NAS) and Susquehanna (CB) rivers and internal dynamics (circulation and biogeochemical processes).

The two systems also differ in their bathymetry. The mean depth of CB is 8.4 m but 33.5 m in the NAS

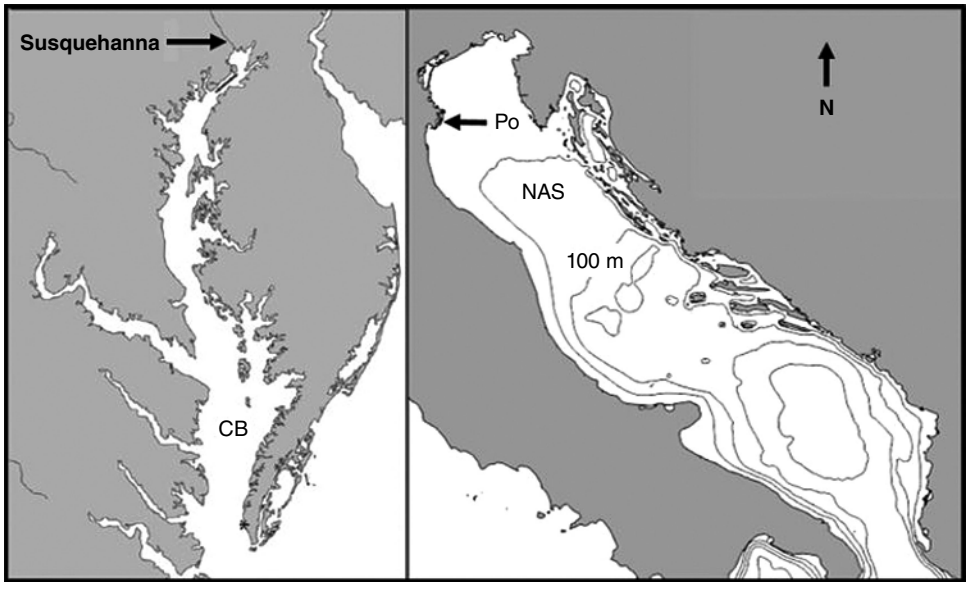

Figure 1.1 (Left) The mainstem Chesapeake Bay (CB), which runs 320 km from the mouth of the Susquehanna River to the Atlantic Ocean. (Right) The northern Adriatic Sea (NAS) extends 135 km southeast to the 100 m isobath. The Po is the largest river discharging into the NAS. (Poulain et al. 2001. Reproduced with permission of Springer Nature).

(Table 1.1). Chesapeake Bay is characterized by a shallow (< 10 m) soft bottom that flanks a relatively deep (10–50 m) central channel running the length of the oligohaline (salinity < 5) and mesohaline (salinity 5–18) reaches of the bay. The NAS is a continental shelf subbasin of the Adriatic Sea, the southern border of which is defined by the 100 m isobath (Poulain et al., 2001).

The geomorphology of each of these two systems produces circulation patterns that increase the residence time of riverine inputs of nutrients and, as a consequence, promotes high levels of phytoplankton production and eutrophication in both systems. At the same time, given the large volume of the NAS relative to the input of nutrient-rich Po River water (14 to 1) and the low volume of CB relative to the input of nutrient-rich Susquehanna River water (1.4 to 1), CB is much more susceptible to eutrophication than is the NAS.

As in many coastal ecosystems, increases in land-based nutrient inputs reflect increasing population density and industrial agriculture in their respective watersheds during the course of the Anthropocene (Meybeck, 2003). Although the annual mean volume transported by each of the two rivers is similar and their watersheds are roughly equivalent in area, total nitrogen (TN) and total phosphorus (TP) loads to the NAS are two to three times higher than to CB (Table 1.1). Differences in nutrient input reflect differences in population density (Po watershed ~230 people km^{-2}, Susquehanna ~60 people km^{-2}), areal extent of agricultural development (Po agriculture ~60% of the watershed, Susquehanna agriculture ~30%), and levels of waste-water treatment (more effective P removal in CB). Nonpoint N loads are greater than point sources for both systems, although point sources contribute a greater proportion of TN to the NAS (40%) than to CB (8–28%). The TP load for CB is largely (66%) from nonpoint sources. In comparison, 44–67% of the TP load for the NAS is from point sources.

Nutrient inputs are distributed via currents and mixing among water masses. The mean (residual) circulation of both systems is driven by thermohaline processes, but on scales of days to months this buoyancy-driven seasonal flow is significantly modulated by wind shear (extratropical and tropical storms in CB and boras (cold, dry, katabatic northeast winds that occur most frequently during winter) and siroccos (warm, humid southerly winds that occur most frequently during summer) in the NAS). Differences in spatial dimensions are reflected in the circulation patterns of the two systems, which in turn affect the distributions of nutrients and phytoplankton biomass in both systems.

Since the width of CB is less than the Rossby radius of deformation (the length scale at which rotational effects become as important as thermohaline processes in determining patterns of circulation), lateral gradients in salinity and density are small relative to gradients along its north–south axis and prevailing flows tend to parallel the main channel. Thus, the primary mechanism of nutrient transport is a two-layered, gravitational circulation with seaward flow of the surface layer and landward flow of the bottom layer. In contrast, the width of the NAS exceeds the Rossby radius so lateral (east–west) gradients promote the development of basin wide cyclonic gyres (Figure 1.1). Due to river runoff and heating in the late spring and summer and to autumn–winter cooling, gradient currents are established. This geostrophic response leads to a cyclonic gyre, with a NW current flowing into the NAS along the eastern margin and a SW current flowing out of the NAS along the western margin. The former transports

Table 1.1 Mean riverine inputs and physical and ecological characteristics of CB and the NAS

Riverborne inputs	Po River	Susquehanna River
Freshwater input (km^3 $year^{-1}$)	46	36
Total N input (10^6 kg $year^{-1}$)	164	63
Mean total P input (10^6 kg $year^{-1}$)	8.8	2.8
Mean NO_x input (10^6 kg $year^{-1}$)	105	43
Mean dissolved inorganic P input (10^6 kg $year^{-1}$)	3.0	0.4
Physical characteristics	**NAS**	**CB**
Length × mean width (km)	135 × 135	320 × 20
Mean depth (m)	33.5	8.4
Surface area (km^2)	18,900	6500
Volume (km^3)	635	50
Surface area/volume (km^{-1})	30	130
Dominant circulation pattern	Cyclonic gyres	Partially stratified, estuarine
Euphotic zone depth (m)	10–55	3–10
Phytoplankton	**NAS**	**CB**
Mean surface chlorophyll-*a* (μg L^{-1})	1.5	9.5
Mean phytoplankton production (g C m^{-2} $year^{-1}$)	90	450

Note: NO_x = dissolved nitrate + nitrite.

warmer and saltier water into the NAS while the latter transports cooler, fresher water out of it. In late fall and winter, the nutrient-rich Po outflow hugs the Italian coast forming a coastal boundary layer of buoyant water when most of the basin is vertically mixed. As the seasonal pycnocline sets up during spring and summer, the Po outflow tends to spread eastward across the basin resulting in longer residence times of nutrients.

The parameters of nutrient recycling via pelagic–benthic interactions include net phytoplankton production, deposition of particulate organic matter (POM), benthic respiration, and benthic nutrient regeneration. While phytoplankton production is fivefold higher in CB than in the NAS, benthic community carbon respiration rates are fourfold higher in CB than in the NAS and differences in sediment nitrogen recycling rates (as NH_4^+) are sevenfold to 15-fold higher in CB. At the same time, rates of denitrification are nearly identical in the two systems. Thus, when normalized to the rate of respiration, the rate of denitrification (and potential loss of nitrogen to the atmosphere via the release of nitrous oxide and dinitrogen gas) is much higher in the NAS than in CB.

1.2.3. Effects of Nutrient Enrichment

1.2.3.1. Phytoplankton Production

Annual cycles and interannual variability of phytoplankton biomass and primary productivity in CB and the NAS are driven by variations in riverine inputs of buoyancy and nutrients. Differences in circulation patterns and geomorphology are reflected in contrasting patterns and levels of eutrophication. Despite having a much lower annual nutrient load than the NAS, annual phytoplankton production is five times higher in CB than in the NAS. Chesapeake Bay is eutrophic system-wide while eutrophication in the NAS is confined to the western NAS, which is directly influenced by the Po River. Receiving waters of CB effectively sequester riverborne nutrient inputs into phytoplankton biomass, and efficiently retain and recycle phytoplankton biomass produced in spring (dominated by diatoms) to support high primary productivity during summer. The seasonal accumulation of biomass during spring also fuels the annual occurrence of extensive bottom-water oxygen depletion during summer in CB. In contrast, seasonal increases in phytoplankton biomass and primary productivity are much lower in the NAS, and bottom-water oxygen depletion is more sporadic in time and space—patterns that reflect the rapid dilution of riverborne nutrient inputs in the NAS. Dinoflagellate blooms occur most frequently under stratified conditions in both systems. However, in contrast to CB, the formation of large organic aggregates in the NAS ("mare sporco") during some years displaces the normally frequent dinoflagellate blooms of the summer.

Since 1729, mare sporco following the spring diatom bloom occurred relatively infrequently (1729, 1872, 1880, 1903, 1930, 1949) compared with the late 1970s through the 1990s (1976, 1983, 1988, 1989, 1991, and 1997), perhaps as a consequence of nutrient enrichment, i.e., they tend to occur under high phytoplankton production, fueled by Po River nutrient inputs during spring and summer, leading to the formation of mucus mats that are transported eastward resulting in episodic deposition of POM and the development of isolated patches of bottom-water anoxia. The location of these mass mortalities varies throughout the season and from year to year, but their cumulative impact results in widespread benthic mortalities in the NAS.

1.2.3.2. Shallow Water Habitats

Like many sublittoral zones worldwide, both systems have experienced dramatic declines in the spatial extent of tidal marshes and submerged aquatic vegetation (seagrass meadows and indigenous macroalgae) as a consequence of cultural eutrophication, coastal development, and sea-level rise. In this regard, it is noteworthy that relative sea-level rise (due to both subsidence and eustatic sea-level rise) is similar in both systems (1.2–8.5 mm $year^{-1}$ in the NAS and 3.2–4.7 mm $year^{-1}$ in CB). Seagrass meadows that once covered ~190 km^2 in the north and eastern NAS began to disappear in the 1970s. Today only isolated patches exist in scattered locations in the eastern NAS. Likewise, seagrass meadows, once abundant in CB (~750 km^2), have been in decline since 1972 when runoff from a tropical storm transported massive amounts of nutrients into the bay. In 1984, seagrass area was estimated to be ~160 km^2. This sustained loss of seagrass habitat during the 1970s and 1980s was primarily due to nutrient enrichment and associated growth of phytoplankton and epiphytic algae that reduced the amount of light available to the grasses. In the NAS, kelp and seagrass meadows along the eastern margin are being lost with some being replaced by turf forming species.

1.2.3.3. Planktonic Consumers

The abundances of microzooplankton populations in the NAS and CB differ in magnitude but exhibit similar seasonal patterns. Both systems develop spring ciliate maxima in response to increases in phytoplankton biomass, however, species composition and the importance of ciliate trophic guilds in respective blooms are dissimilar. Dominance of spring blooms by distinct trophic guilds appears to reflect divergent levels of eutrophication and may translate into different ecological roles for microconsumers in the two regions.

Periodic outbreaks of large scyphomedusae, *Chrysaora quinquecirrha* in CB and *Pelagia noctiluca* in the NAS, may be related to nutrient enrichment and over fishing, but this has yet to be confirmed. Both species consume zoo-

plankton and ichthyoplankton and are detrimental to fish stocks because they consume their food and prey on their young. Given their abundance in both systems, these gelatinous species may be important in nutrient recycling and in determining the structure of pelagic food webs. In addition, they have painful stings and negatively affect tourism.

1.2.3.4. Benthic Animals

Sessile macrobenthic animals exhibit varying degrees of stress, including death, in response to oxygen depletion. Their exact response depends on the duration and severity of the oxygen depletion and the pattern of exposure. Although seasonal bottom-water oxygen depletion occurs in both systems, the spatial pattern and temporal extent differs. In CB, hypoxia occurs throughout the mesohaline reach for several weeks each summer, while bottom-water hypoxia in the NAS occurs in different locations each year and for shorter periods than in CB. Thus, macrobenthic species that grow in those reaches of CB that experience seasonal hypoxia are r-selected (species with high growth rates that exploit less-crowded niches, and produce many offspring) enabling rapid recovery between events. Such recovery does not occur in areas of the NAS originally dominated by slow growing, long-lived epibenthic species. In these locations small-scale community extirpations begin to merge, thereby exerting a cumulative effect by reducing benthic biomass and species diversity over increasingly large areas.

1.2.3.5. Fisheries

Recent annual landings have been ~100,000 in the NAS and ~275,000 tons in CB, a contrast that may reflect differences in phytoplankton production. Clupeoid fishes (anchovies, sardines, or menhaden) dominate fish biomass and catch in both ecosystems. Fisheries on anadromous and estuarine-dependent species are more important in CB while diverse, demersal fisheries are relatively more important in NAS. Although total catches have remained high, anchovy stocks in the NAS collapsed in the 1980s.

In CB, oyster stocks declined rapidly during over the past five decades due to overfishing and disease, a trend that reduced their capacity to prevent accumulations in phytoplankton biomass and exacerbated the effects of anthropogenic nutrient enrichment on phytoplankton biomass and the magnitude of bottom-water anoxia. In the NAS, fishing practices hinder the reestablishment of natural benthic communities. Thus, both systems would benefit from management actions that both reduce nutrient loadings and enhance natural benthic communities.

1.2.4. Management

Eutrophication, overfishing, and problems of interjurisdictional management are common to both systems. The most comprehensive program to improve the water quality of CB was launched in 1983 (1st Chesapeake Bay Agreement) to reduce point and nonpoint nutrient inputs as a means of restoring the bay to a healthy ecosystem. In 1987, the Agreement was strengthened by specifying a quantitative target for nutrient reduction, i.e., achieve a 40% reduction in controllable nutrient (N and P) inputs by the year 2000. Two hallmarks of this agreement are (a) the implementation of a monitoring program to assess the relationship between changes in land cover using satellite-based imagery and (b) whole watershed modeling to guide best management practices to limit both point and nonpoint inputs of anthropogenic nutrients, and quantify distributions of water quality parameters in time and space.

Recent progress in development of national and international management accords (Slovenia, Croatia, Italy) began with the establishment of the Po River Authority by Italy in 1989 and the release of the Po Master Plan that articulated seven major objectives:

1. control the impacts of floods and coastal erosion;
2. identify subsidence areas and sources of pollution and determine management options for each;
3. restore river flow for mitigating floods;
4. monitor aquifer recharge and pollutant spread by ground water;
5. develop water-use priorities based on human and ecological needs;
6. develop predictive models of the basin-wide hydrological cycle;
7. formulate regional plans and develop a data base for the NAS.

The existing water quality and hydrology monitoring network for the Po subbasin provides a good foundation on which these monitoring and modeling programs can build.

Quantitative assessment of nutrient management strategies will require an improved understanding of the details of circulation transport pathways throughout the seasonal progression of atmospheric forcing and of buoyancy and nutrient inputs in both water bodies. Crucial questions remain, many of which center on physical–biological interactions in the vertical dimension. In the NAS, a key question is the mechanism and degree of lateral transport of water and nutrients out of the Po River plume and into the sea's interior. In both CB and the NAS, coupled physical–biological models are needed to address these problems. Analytical efforts in CB have been supported by a rich set of synoptic, time-series measurements. Similar modeling efforts in the NAS have progressed without the benefit of this level of observation, and the pace of future advancements will hinge on obtaining this information.

The need for ecosystem-based management of fisheries is similar in CB and the NAS. Sustained, cost-effective, ecosystem-based management of nutrient loading, water

quality, and fisheries is a major challenge to government agencies responsible for protecting the environment and managing living resources in both systems. This synthesis illustrates the importance of sustained research, monitoring, and modeling to the design, implementation, and improvement of ecosystem-based approaches to addressing this challenge. A related challenge is presented by the reality that the boundaries of ecosystems and movements of pelagic animals do not obey political jurisdictions. Thus, international collaboration is needed to address this challenge in the NAS, while interstate collaboration is needed for CB.

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