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Eutrophication of Estuarine and Coastal Marine Environments: An Emerging Climatic-Driven Paradigm Shift

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Abstract

Estuaries and coastal marine waters are complex dynamic environments that are susceptible to the stresses and vagaries of climatic and non-climatic drivers of change. Climate change is an increasingly important factor in the development of eutrophication in estuarine and coastal marine environments. The additive, synergistic, and antagonistic interactions of climatic drivers of change and non-climatic anthropogenic and natural stressors create deleterious conditions that degrade these environments and their biotic communities. Climate-change mediated increases in precipitation, land runoff, river discharges, and temperature result in greater nutrient and organic matter loading, biogeochemical fluxes, enhanced thermal and salinity stratification, altered water circulation, harmful algal blooms, water column light attenuation, and deteriorated sediment and water quality in many estuarine and coastal marine ecosystems. The frequency, intensity, and extent of hypoxia are increasing in these ecosystems as well, where climate change amplifies the effects of eutrophication, leading to deoxygenation and extensive mortality of benthic organisms, a decline of fisheries, and damage to essential habitats. As temperature, nutrient enrichment, and organic matter supply continue to increase in many coastal regions worldwide, there are greater costs incurred for mitigation, adaptation, and resilience programs needed to deal with their adverse effects to improve the viability and sustainability of estuarine and coastal marine ecosystems, especially in urbanized areas. Coastal ecosystems are in a state of flux driven by climatic forcings that are causing a paradigm shift in their assessment and management. To this end, coastal managers are implementing ecosystem-based management programs using holistic, multidisciplinary integrated and unifying frameworks that link ecological, physical, and socio-economic elements to address the causes, consequences, and responses of anthropogenic impacts to maintain estuarine and coastal marine ecosystems in a healthy, productive, and resilient condition.

Keywords

Coastal Ecosystems, Anthropogenic Activities, Climate Change, Nutrient Enrichment, Organic Matter Loading, Eutrophication, Hypoxia, Interactive Factors, Ecosystem Impacts, Assessment, Management

1. Introduction

Climate change is increasingly hazardous to coastal ecosystems, amplifying the effects of eutrophication and other non-climatic stressors that are causing a decrease in ecosystem services and societal goods and benefits to humankind [1]-[11]. Eutrophication is an insidious degrading process interactive with climatic drivers of change that causes serious escalating problems in estuarine and coastal marine environments traceable to human population growth, land development, and other anthropogenic activities in coastal regions. Of particular note are anthropogenic activities that forge land-use and land-cover changes, modifications of hydrologic regimes, and greater inputs of nutrients and organic matter to coastal waterbodies. These aquatic environments are characterized by highly variable conditions often linked to intense human-mediated alteration of physical, chemical, and biological processes [12]-[19]. Anthropogenic activities on land or in the sea generate endogenic and exogenic pressures (*i.e.*, mechanisms of change) that are agents of ecosystem impacts. A major challenge is to address and effectively manage the cumulative adverse effects of the anthropogenic activities impacting ecosystem structure and function [4] [20]-[22]. Ecosystem-based management and governance are necessary elements to maintain the integrity and sustainability of these vital coastal environments and their services [18] [22]-[26].

This article examines the interaction and impact of climatic drivers of change and eutrophication on estuarine and coastal marine environments. Climate change is defined as regional or global changes in mean climate state or in patterns of climate variability over decades to millions of years often identified using statistical methods, and sometimes referred to as changes in long-term weather conditions [27] [28]. Estuarine and coastal marine ecosystems are changing with escalating climate-induced temperature increases, sea level rise, and nutrient and organic matter loading that are modulating shifts in ecosystem structure and function.

2. Coastal Ecosystem Susceptibility

Estuaries and coastal marine waters are susceptible to the vagaries of natural stressors and the impacts of anthropogenic activities that can create deleterious environmental conditions [1] [6] [8] [14] [15] [29] (**Table 1**). Numerous physical,

Table 1. Major anthropogenic drivers of change in estuarine and coastal marine environments. Modified from Kennish (100).

Drivers
Class 1 (Degrade Water Quality)
Nutrient Overenrichment and Organic Carbon Loading
Thermal Loading
Biogeochemical Changes
Chemical Contaminants
Excessive Sediment/Particulate Inputs
Sewage Discharges
Pathogens
Class 2 (Impact Habitat)
Watershed Development
Land-Use and Land-Cover Changes
Marinas and Other Facilities
Dredging and Dredged-Material Disposal
Mineral Resource Extraction
Bottom Trawling
Dams and Other Obstructions
Shoreline Hardening
Lagoon Construction
Land Reclamation and Impoundments
Coastal Subsidence
Class 3 (Alter Biotic Communities)
Altered Watershed Hydrological Regimes
Overfishing
Intensive Aquaculture
Invasive/Introduced Species
Floatables/Plastics/Debris
Class 4 (Climate Linked)
Climate Change Drivers
CO_2, CH_4, NO_2, Chlorofluorocarbons, (Greenhouse Gases)
Warming Temperatures
Precipitation and Land Runoff
Altered Winds and Water Circulation
Acidification
Extreme Events
Heatwaves
Hurricanes and Other Major Storms
Storm Surges
Tornadoes
Droughts

chemical, and biological factors occur along the freshwater to marine continuum that typically overlap in space and time resulting in cumulative interactive effects, including climatic drivers of change that modulate ecological conditions and impact the structure and function of ecosystems [4] [6] [7] [11] [19] [22]. Increased storm intensity and precipitation, land runoff, river discharges, and warming waters driven by climate change are leading to greater nutrient and organic matter loading, biogeochemical fluxes, harmful algal blooms (HABs), water column stratification and light attenuation, altered circulation, and deteriorated sediment and water quality in estuarine and coastal marine ecosystems [30]-[35]. These factors interacting with other anthropogenic stressors cause significant shifts in organism abundance and productivity, reproduction, phenology, distribution, and food web dynamics. Sea level rise affects water depth, tidal range, salinity, sediment distribution, intertidal and subtidal habitats, and other components of shallow coastal ecosystems. The complexity of the aforementioned interacting factors, the limited databases collected on them, and insufficient use of predictive models generated for specific estuaries and coastal marine waters have created significant challenges for scientists and coastal managers attempting to unravel the array of ecosystem impacts associated with the interactive effects of climatic drivers of change, nutrient enrichment, and organic matter loading in estuarine and coastal marine environments [10].

Multiple and diverse stressors interact additively, synergistically, and antagonistically in estuarine and coastal marine environments [4] [11] [20] [22] [36]. Climatic drivers of change interact with multiple non-climatic anthropogenic stressors to induce pressures in a cumulative way that generate degrading conditions in estuarine and coastal marine environments [37]. For example, the frequency, intensity, and extent of hypoxia are increasing in estuarine and coastal marine waters, where climate change amplifies effects of eutrophication [17] [19] [38]-[41]. Hypoxia and anoxia of bottom waters have devastating impacts on estuarine and marine organisms, often resulting in extensive loss of life in benthic communities and declining fisheries as well as damage to habitats [42]-[44].

It is important, therefore, to assess climatic drivers of change, together with interactive anthropogenic non-climatic stressors such as eutrophication, to delineate and accurately assess the impacts on coastal environments, most notably those affecting physical-chemical conditions and the structure and function of biotic communities. Coastal scientists face significant challenges with such highly variable, interactive, persistent, and damaging drivers of change. This paper focuses on one of these challenges, that is, the effects of climatic drivers of change on eutrophication of estuarine and coastal marine environments, which are causing marked changes in ecosystem condition and sustainability.

3. Coastal Climatic Forcings

Anthropogenic climatic forcings, primarily those factors linked to an inability to curb greenhouse gas emissions (notably carbon dioxide, nitrous oxides, and methane), as well as deforestation and watershed land-use and land-cover changes have increased air and water temperatures and altered biogeochemical cycling and other coastal processes [19] [29] [45]-[47]. As noted previously, climatic forcings have profound effects on freshwater inflow to coastal waterbodies, water column stratification, circulation and mixing, and the distribution of organisms. Modified coastal landscapes and hydrologic systems (e.g., freshwater diversions, river channelization, and dredging) have facilitated nutrient and organic matter loading from point and nonpoint sources into estuarine and coastal marine waters, promoting eutrophication and hypoxia formation and leading to altered ecosystem structure and function [10] [17] [18] [40]. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) documented regional and global impacts of climate change on natural and human systems, including increasingly irreversible biotic and habitat losses in estuarine and coastal marine waters and reduced services they provide [48]. These impacts have been linked directly to greater greenhouse gas emissions (notably CO_2), higher global temperatures, sea level rise, increasing nutrient inputs, and decreasing ocean pH levels (acidification). According to Wong *et al.* (49), coastal ocean acidification driven by climate change is greater in areas affected by eutrophication.

The 2015 Paris Climate Agreement, an international accord on climate change signed by 195 countries, set a long-term goal to limit the increase of global average temperature on Earth to well below 2˚C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5˚C above pre-industrial levels. Limiting the global average temperature increase as stated by the Paris Climate Agreement should substantially reduce the environmental risks and effects of climate change on coastal, estuarine, and marine organisms and habitats. Coastal ecosystems are increasingly challenged by major anthropogenic stressors, such as climate change and eutrophication, that require greater focus of management programs to maintain their viability and sustainability [18] [22] [24]-[26]. As global temperature, nutrient enrichment, and organic matter supply continue to increase in many coastal regions, there are greater costs incurred for mitigation, adaptation, and resilience programs needed to deal with their adverse effects, especially in urbanized areas. These programs are necessary to ensure the health of coastal ecosystems and the effectiveness of remediation efforts to prevent their transformation in the face of climate change and other anthropogenic stressors [5] [6] [16] [26].

The record-breaking temperatures on Earth during the past decade have generated a new immediacy to the global existential threat of climate change. Greenhouse gas emissions, largely responsible for increasing global temperatures, reached a record high in 2024, which was also the warmest year on record by far since global temperature records began in 1850, according to the NOAA National Centers for Environmental Information (NCEI). According to the European Union's Copernicus Climate Change Service (C3C), this was the first ever 12-month period in which the global average surface air temperature increase exceeded the 1.5˚C temperature threshold above the pre-industrial level, reaching 1.6˚C for the year (**Figure 1**). As conveyed by the C3C, high sea surface temperatures were a significant driver of the elevated annual air temperature anomaly registered for 2024 (Table 2, Figure 2). While 2024 was the warmest year on record (global average surface air temperature 15.10˚C) dating back to 1850, the global average surface air temperature in 2023 was also high (14.98˚C), resulting in a two-year average temperature anomaly for 2023-2024 that exceeded the 1.5˚C temperature threshold as well. Furthermore, the past decade has been the warmest 10-year period in the 175-year climate record of NOAA (NCEI).

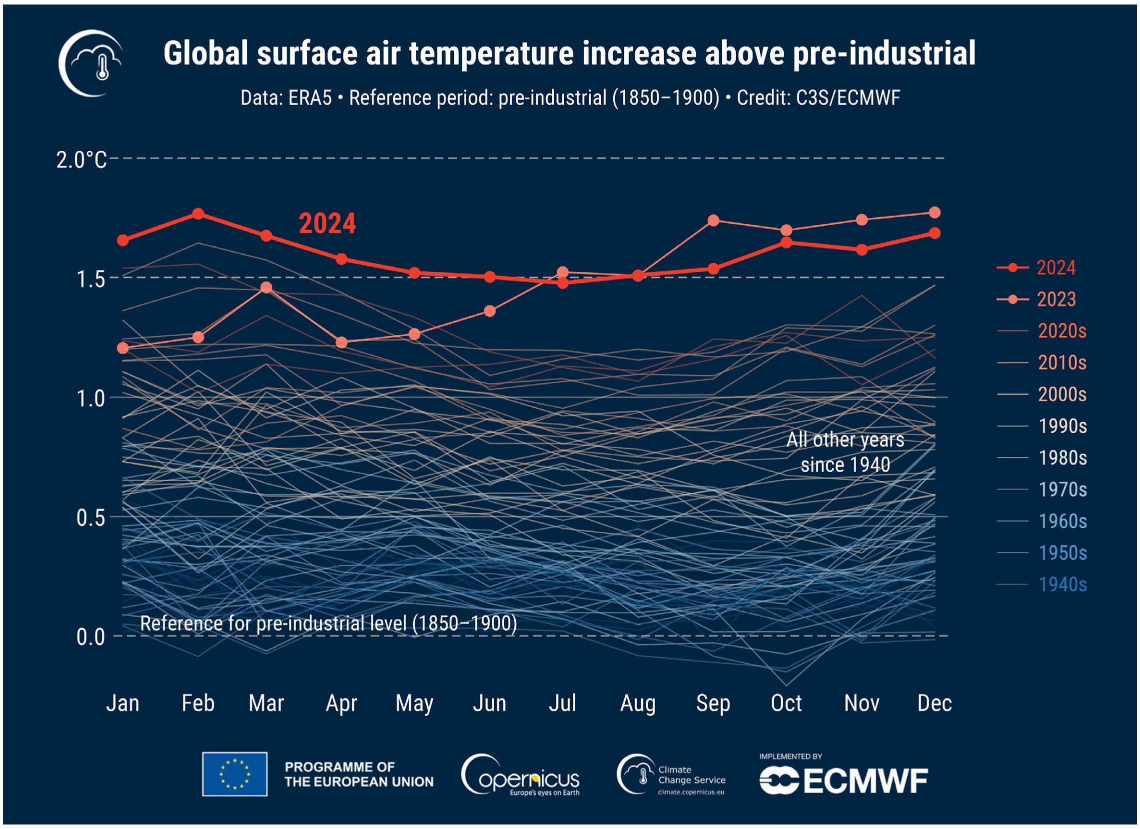

Figure 1. Global surface air temperature increase (˚C) above the average for the pre-industrial reference period (1850-1900) for each month from January 1940 to December 2024, plotted as time series for each year. 2024 is shown as a thick red line and 2023 as a thick pink line, while other years are shown with thin lines and shaded according to the decade, from blue (1940s) to red (2020s). Credit: Copernicus Climate Change Service (C3S)/European Centre for Medium-Range Weather Forecasts (ECMWF). Global Climate Highlights 2024. Source: https://climate.copernicus.eu/copernicus-2024-first-year-exceed-15degc-above-pre-industrial-level.

Table 2. Key temperature statistics of the European Union's Copernicus Climate Change Service for 2024.

Region	Anomaly (vs. 1991-2020)	Actual Temperature	Rank (out of last 85 years)
Globe	+0.72˚C (+1.60˚C vs pre-industrial)	15.10˚C	1st
Europe	+1.47˚C	10.69˚C	1st
Arctic	+1.34˚C	−11.37˚C	4th highest
Extra-Polar Ocean	+0.51˚C	20.87˚C	1st

Credit: Copernicus Climate Change Service (C3S)/European Centre for Medium-Range Weather Forecasts (ECMWF). Global Climate Highlights 2024.

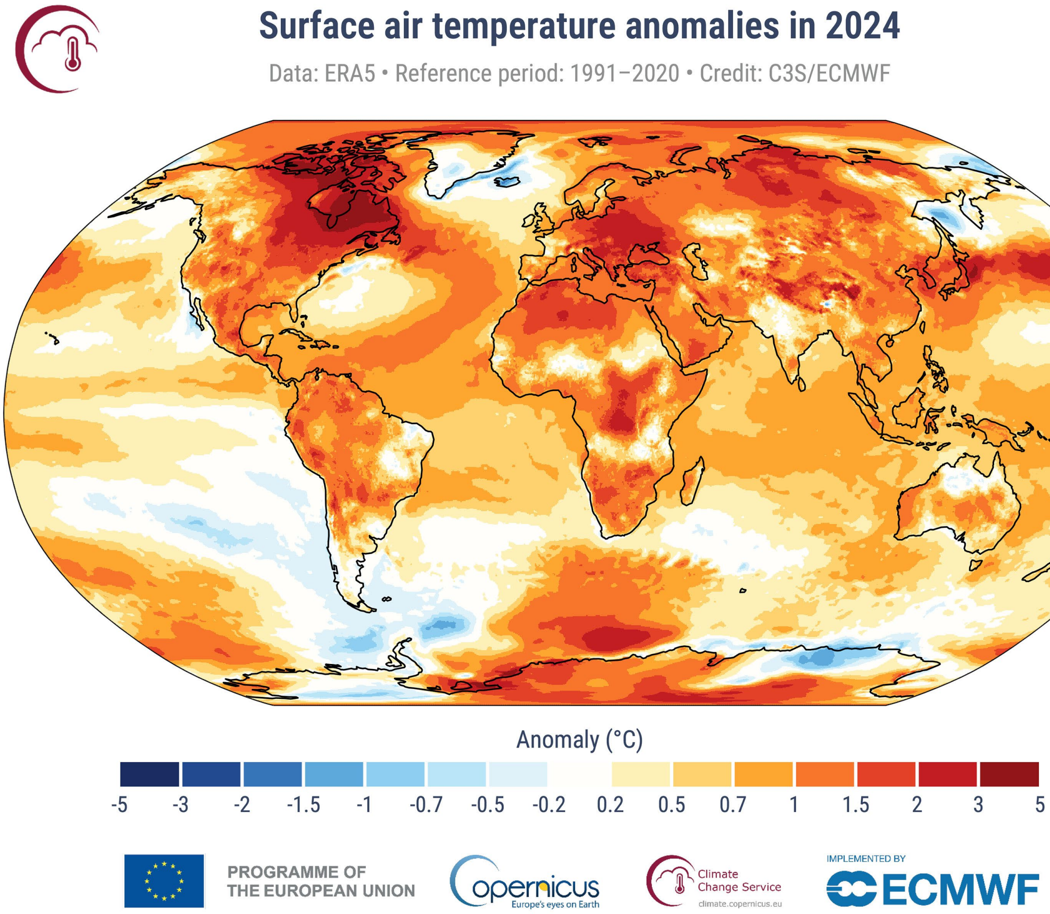

Figure 2. Surface air temperature anomalies on Earth for 2024 relative to the average for the 1991-2020 reference period. Data: ERA5. Credit: Copernicus Climate Change Service (C3S)/European Centre for Medium-Range Weather Forecasts (ECMWF). Global Climate Highlights 2024. Source: https://climate.copernicus.eu/copernicus-2024-first-year-exceed-15degc-above-pre-industrial-level.

The oceans are a major carbon sink and a significant driver of rising global temperatures. The bulk of the aforementioned temperature rise has been borne by the same oceans that absorb ~30% of CO_2 emissions; sea surface temperatures have risen as the oceans absorbed ~90% of excess heat stemming from the greenhouse gas emissions. **Figure 3** shows sea surface temperature anomalies recorded during 2024. C3C found that the average sea surface temperature (SST) over the extra-polar ocean (between 60˚N - 60˚S) reached a record high of 20.87˚C in 2024. Highest average SST values were recorded in the North Atlantic, Western Pacific, and the Indian Ocean, although most ocean basins had higher than average SST values as well. El Niño Southern Oscillation (ENSO) warming conditions contributed to higher sea temperatures particularly in 2023, while a residual effect extended into the first six months of 2024.

In 2023, the second warmest year on record, the global average land and sea surface temperature was 1.18˚C above the 20th century average of 13.9˚C, as noted by NOAA (NCEI). More than 90% of the warmest years on record have occurred since 2000, reflecting the growing threat of global warming. Since 1850, CO_2 concentrations in the atmosphere alone have increased dramatically, mainly due to burning of fossil fuels, rising from approximately 285 parts per million (ppm) to more than 422 ppm at the end of 2024, and likely reaching their highest level in the last 15 million years (NOAA-NCEI). Due to increasing greenhouse gas emissions (mainly CO_2), ocean acidification is on the rise as well, threatening corals and other shell-bearing organisms in the sea [45] [46]. To avert the most serious damaging effects of climate change on coastal, estuarine, and marine environments, there is a goal to achieve net-zero CO_2 emissions globally by 2050.

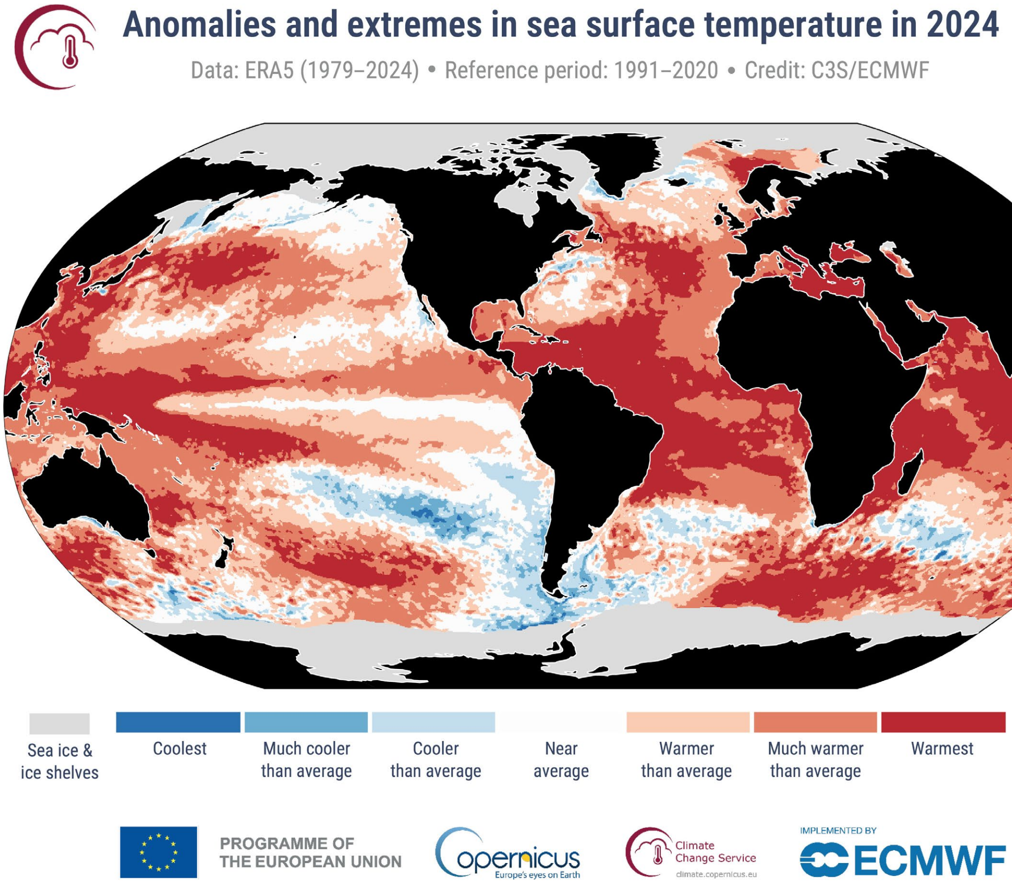

Figure 3. Anomalies and sea surface temperature extremes for 2024. Color categories refer to the percentiles of the temperature distributions for the 1991-2020 reference period. The extreme ("coolest" and "warmest") categories are based on rankings for the period 1979-2024. Values are calculated only for the ice-free oceans. Data source: ERA5. Credit: Copernicus Climate Change Service (C3S)/European Centre for Medium-Range Weather Forecasts (ECMWF). Global Climate Highlights 2024. Source: https://climate.copernicus.eu/copernicus-2024-first-year-exceed-15degc-above-pre-industrial-level.

The rate of ocean warming has more than doubled since 1993, with most ocean warming occurring since 1980 [49]-[51]. Of great concern are marine heatwaves (*i.e.*, sustained periods of anomalously high near-surface temperatures that can lead to severe and persistent impacts on marine ecosystems), which have doubled in occurrence since the 1980s [52]. They are projected to increase in frequency, duration, and intensity this century with continued climate change [50]. Rising sea temperatures pose an increasing threat to estuarine and coastal marine ecosystems, which rank among the most productive aquatic environments on Earth, providing substantial ecosystem services, goods, and benefits (e.g., recreational and commercial uses, seafood and pharmaceutical products, energy production and coastal protection) for multitudes of people worldwide.

The rate of sea surface temperature increases along coastlines has been greater than that of the open ocean, indicative of the more pressing problems of climate change effects on ecosystems in coastal regions [29] [49]. For example, Lima and Wethy [53] found that over the period from 1982 to 2010 coastal sea surface temperatures increased for more than 71% of the world's coastlines at a rate of 0.25˚C ± 0.13˚C per decade. In addition to record-breaking temperatures, 2024 exhibited high-intense and destructive tropical and extratropical cyclones as well as other coastal storms accompanied by storm surges that impacted estuarine and coastal marine ecosystems, their watersheds, and nearby built communities. The intensity of major tropical cyclones is increasing due to climate change [8] [9] [19] [49].

The structure and function of estuarine and coastal marine ecosystems are experiencing more intractable changes as temperatures gradually rise and persist above the 1.5˚C temperature threshold noted by the IPCC, including reductions in species abundance, diversity, and fisheries production as well as altered habitats in many regions [45] [46]. Rising temperatures affect the physiological and reproductive processes of estuarine and marine organisms as well as their growth and survival rates [14] [54] [55]. In addition, increasing eutrophication and associated hypoxia/anoxia (hypoxia < 2.0 mg O_2 L^{-1}, anoxia < 0.5 mg O_2 L^{-1}), influenced in part by rising temperatures together with acidification of susceptible waterbodies, are detrimental to ecosystem function [10] [17]. Furthermore, global warming is promoting the occurrence of toxic, food-web disrupting nuisance and HABs as well as invasive species in coastal ecosystems, which will only worsen with higher temperature increases [19]. The number and expanse of hypoxic zones in estuaries and coastal seas have increased substantially with rising global temperatures and greater eutrophication [17] [39]-[41] [43] [56]-[59]. Dissolved oxygen levels in the sea will decline further with increases in global temperatures this century [50]. Ecosystem services of estuarine and coastal marine ecosystems also will decline with continued global warming, such as fisheries and mariculture, likely leading to food insecurities in some countries as well as diminished tourism and recreational uses in regions worldwide.

Many built communities along coasts are experiencing greater intensity and frequency of extreme weather events and storm surge effects, higher precipitation with nutrient- and organic-enriched river discharges that promote eutrophication, accelerated erosion of beaches and receding shorelines due to sea level rise, and more droughts and heatwaves. Global precipitation over land areas has increased at an average rate of 0.076 cm per decade since 1901 [60]. Climate model forecasts not only predict increased precipitation in the decades ahead but also significant increases in intensity of heavy rainfalls in some regions which will accelerate runoff and freshwater flow into estuaries and coastal marine waters [28]. Other projections reveal regional variations in precipitation, greater storm surges and coastal flooding in areas of heavy precipitation, higher salinity intrusion and coastal erosion, and more coastal community infrastructure damage.

Melting glaciers and ice sheets, as well as thermal expansion of the ocean due to absorption of heat, are accelerating sea level rise, inundation, flooding, increased coastal erosion, salinity intrusion, drowning of wetlands habitat, and loss of coastal infrastructure [46] [49] [61]. Between 1901 and 2018, eustatic mean sea level increased by 20 cm [52], and climate models predict a 40 to >200 cm eustatic sea level rise over the next 100 years [10]. Sea level rise is not globally uniform, but regionally variable, and it therefore poses a greater coastal threat to some regions than others [50].

4. Climatic and Anthropogenic Driver Interactions

Climate change affects nutrient inputs and behavior in estuarine and coastal marine waters by altering temperature, wind, storm occurrence and intensity, hydrologic cycles, water circulation, and sea level rise [2]. Anthropogenic nutrient enrichment and organic matter loading have been increasing in waterbodies along the freshwater to marine continuum since the 1950s, although the interaction of climate change and nutrient enrichment is complex [19] [62]. More data are needed on the effects of multiple anthropogenic factors that interact in a waterbody and alter the structure and function of biotic communities and impact habitats. Medina *et al.* [63] demonstrated the effectiveness of tracking symptoms of eutrophication over a 22-year period using multiple lines of evidence in a study of the Charlotte Harbor estuary in southwest Florida (USA). Kennish [6] reported that additive, synergistic, and antagonistic interactions of climatic drivers of change and non-climatic anthropogenic stressors are causing significant biotic changes in estuarine and coastal marine waters. Some of the most overt biotic changes are evident in coastal wetlands—salt marshes, mangroves, and seagrasses [5] [64] [65].

Table 3 provides a list of major interactive factors of climate change and non-climatic stressors that contribute to eutrophication development in estuarine and coastal marine environments. An important challenge is determining how climate change forcings interact with nutrient and organic matter loading, freshwater discharges, flushing, and water circulation to alter ecosystems along the freshwater to marine continuum [8] [33] [66]-[68]. Altered frequency, intensity, and timing of precipitation and variable hydrologic conditions linked to climate change are contributing to pulsed nutrient and organic matter delivery as well as modified water column stratification and flushing/residence time in estuaries. These fluxes cause significant changes in nutrient concentrations, primary productivity, and dissolved oxygen levels which influence trophic level dynamics [35] [62] [69]. The flux of hydrologic processes and sea level are affecting biotic communities, habitats, and ecosystem stability [8]. Testa *et al.* [10] noted that most climate-prediction scenarios of increased global CO_2 levels also reflect regional changes in precipitation and storm frequency. For a RCP8.5 "business-as-usual" climate model scenario, Sinha *et al.* [70] showed that climate-change induced precipitation alone will substantially increase total nitrogen loading in US rivers by 19% ± 14% during this century. In addition, climate change will have a greater effect on dissolved oxygen via altered atmospheric and aquatic forcing effects in coastal environments (*i.e.*, temperature, wind, water column stratification, and water circulation).

Table 3. Major interactive factors of climate change, altered land and hydrologic systems, and eutrophication that exacerbate impacts on estuarine and coastal marine ecosystems.

Factor	Impact
Warming Temperatures	Strengthened Pycnoclines; Reduced Oxygen Transmission to Deeper Waters; Decreased Nutrient Recycling to Surface Waters; Increased Phytoplankton and Vascular Plant Growth and Biomass
Heatwaves and Droughts	Decreased Oxygen Solubility
Coastal Fires	Increased Runoff of Nutrients and Organic Matter to Coastal Waters from Altered Land Surfaces
Sea Level Rise	Coastal Land Inundation and Erosion; Increased Nutrient and Organic Matter Delivery to Estuarine and Coastal Marine Waters
Storm Surges and Tidal Flooding	Increased Inundation and Erosion; Runoff of Nutrients and Organic Matter to Streams and Rivers
Higher Intensity Storms	Freshwater Runoff Pulses; Higher Nutrient and Organic Matter Delivery to Estuaries and Coastal Marine Waters
Greater Precipitation (10% - 20%)	Increased Land Runoff; Higher Nutrient and Organic Matter Delivery to Estuaries and Coastal Marine Waters
Land-Use and Land-Cover Changes (Increased Impervious Surfaces)	Higher Nutrient and Organic Matter Runoff to Streams and Rivers
Increased Land Runoff	Higher Nutrient and Organic Matter Delivery to Estuaries and Coastal Marine Waters
Modified Hydrologic Regimes	Variable Delivery of Nutrients and Organic Matter Supply to Estuaries and Coastal Marine Waters
Higher River Discharges	Greater Nutrient and Organic Matter Loading to Estuarine and Coastal Marine Waters
Altered Flushing and Water Residence Time	Variable Concentrations of Nutrients and Organic Matter Supply in Estuarine Waters
Increased Water Column Stratification	Reduced Vertical Mixing and Oxygen Delivery to Bottom Waters; Decreased Water Column Nutrient Distributions
Water Circulation Changes	Variable Distribution of Nutrients and Organic Matter Supply
Increased Wind Velocity	Greater Water Column Mixing and Distribution of Nutrients and Organic Matter

With ongoing climate change modulation of key processes in estuarine and coastal marine environments, it is vital for management programs to develop the initiatives necessary to mitigate the resulting impacts and improve environmental conditions. To this end, ecosystem-based management using a holistic, multidisciplinary integrated approach that links ecological, physical, and socio-economic systems for the protection and sustainability of these coastal environments is favored [18] [22] [24] [25] [71]-[73]. The entire airshed/watershed to coastal ocean continuum should be addressed by this type of management approach. An example of a relevant nutrient management strategy is that advanced by Paerl *et al.* [33] for the Neuse River-Pamlico Sound system in North Carolina (USA) that considers holistically the timing of fertilizer applications in coastal watersheds, stormwater controls coupled to climate change, wastewater nutrient releases, no-till agricultural practices, agricultural animal waste containment/treatment, and greater coupling and integration of groundwater and atmospheric nutrient sources with estuarine and coastal nutrient budgets and algal bloom dynamics.

5. Eutrophication

There is an established link between climate change drivers and eutrophication development that poses an increasing threat to biotic communities and habitats in estuarine and coastal marine environments [6]-[8] [17] [19] [40] [62] [74]. Nutrient enrichment and organic matter loading in these environments emerged as an escalating ecological problem during the 1960s and 1970s as human population growth and development accelerated in coastal watersheds worldwide, especially in developed nations [75]-[77]. Approximately 40% of the 8 billion human population on Earth now lives within 100 km of the coast [6]. The impacts of interactive and accelerating climate change drivers and non-climatic anthropogenic stressors are leading to a reexamination of the main factors responsible for declining coastal ecosystems (**Table 3**).

Eutrophication is defined as an increase in the rate of organic matter supply to an ecosystem [78] [79] and the development of undesirable consequences that pose a threat to its structure (e.g., biotic community composition, species abundance, and biodiversity) and function (e.g., biotic productivity, energy flow, biogeochemical cycling, and microbial decomposition) [7] [32] [80]. It is a hazardous condition manifested by an array of cascading environmental problems such as HABs, hypoxia and anoxia, loss of essential habitat (e.g., seagrass, salt marsh, and shellfish beds), altered biotic communities, reduced biodiversity, species shifts, declining harvestable fisheries, imbalanced trophic food webs, and diminished resilience of impaired waterbodies [6] [19] [81]-[83]. Nutrient and organic matter supply that promotes eutrophication can have an autochthonous source (*i.e.*, via primary and secondary production in the waterbody) as well as an allochthonous source (*i.e.*, transported into the waterbody from terrestrial and other external sources).

Nutrient inputs to a coastal waterbody stimulate phytoplankton and macrophyte primary production and increase autochthonous organic matter inputs, with the biomass accumulation in bottom sediments raising the biochemical oxygen demand and microbial decomposition of the organic matter. Allochthonous inputs of organic matter (e.g., sewage wastes and organism remains originating outside of the waterbody) amplify the effects. Natural coastal hazards, such as landslides, volcanism, and earthquakes, can deliver pulses of organic matter to estuarine and coastal marine environments as well, potentially stressing ecosystems. Nutrient regeneration via microbial decomposition of organic matter in bottom sediments and resuspension processes increase nutrient concentrations in the water column and stimulate additional primary production, which exacerbates nutrient enrichment and eutrophication effects. Burkholder *et al.* [84] observed that estuarine bottom sediments serve as a secondary source of nutrients for the water column, having concentrations that may be 10- to 100-fold higher than in the water column. Thus, pelagic-benthic coupling plays a significant role in biogeochemical feedbacks that can lead to overenrichment of nutrients in the waterbody exacerbating eutrophication problems [77]. Nutrient overenrichment and organic matter loading problems are frequently observed in waterways near major cities where anthropogenic activities are greatest (e.g., New York City, São Paulo, Tokyo, Cairo, and Stockholm). Eutrophication is a major aquatic pollution problem in the world today, with more than two-thirds of US estuaries alone impacted by it [14] [32] [77].

High inputs of nutrients stimulate phytoplankton and macroalgal blooms, which can increase shading effects, hypoxia, and loss of seagrasses and other phanergams that serve as vital benthic habitats for biotic communities [38] [81] [83]-[86]. Excessively high water temperatures in summer linked to climate-change driven heatwaves can decimate seagrass beds, particularly at species range boundaries where water temperatures approach species thermal tolerance limits, as is evident in *Zostera marina* beds in Chesapeake Bay and other Mid-Atlantic estuaries [13] [86]. These cascading problems cause disruption of system trophodynamics and declining resilience. Consequently, nutrient controls (*i.e.*, nutrient load reductions) implemented along the freshwater to marine continuum are a key strategy of water-quality management programs to remediate adverse effects of nutrient enrichment and organic matter loading. Allochthonous transport systems that deliver nitrogen and phosphorus to estuaries and coastal marine waters are necessary targets for nutrient reduction efforts (*i.e.*, nutrients in land runoff and river discharges, wastewaters, groundwater, and atmospheric deposition). Nonpoint source nutrient inputs are more difficult to control than point sources because they are widely dispersed and temporally variable. While many investigators emphasize the importance of nutrient inputs from land runoff, river discharges, and wastewater systems, others are contending that groundwater and ocean water sources cannot be ignored in eutrophication assessment as well [87] [88]. For example, Rocha *et al.* [88] estimated that 14% of the nitrogen and 3.9% of the phosphorus inputs into agroecosystems arrives at sea via groundwater-borne discharges.

Human-altered physical and biological systems can significantly enhance eutrophication. For example, hydromodifications in coastal watersheds can facilitate nutrient-enriched freshwater discharges to estuaries and coastal marine waters and thus can promote higher primary production in receiving waters. In addition, overfishing may lead to the reduction of top-down grazing pressure and potentially greater phytoplankton and macrophyte growth [74].

Allochthonous nitrogen inputs, originating outside of an estuary, are generally referred to as new nitrogen rather than nitrogen generated autochthonously [89]. The effects of climate change are now augmenting non-climatic, anthropogenic-driven nutrient enrichment and organic matter loading, hypoxia development, and resulting biotic impacts, thereby posing even greater challenges for coastal ecosystem management programs that must deal with both global and local drivers of ecosystem change [2] [58] [66] [69] [74] [90] [91]. Management strategies to control nutrient overenrichment of coastal waterbodies must consider the nutrient sources, concentrations, delivery processes, and effects along the entire freshwater to marine continuum, all of which pose significant challenges to coastal resource managers.

Eutrophication affects the trophic status of an estuary, which can be expressed as a trophic state index (TSI) in units of C per area per unit time organized into four categories (*i.e.*, oligotrophic <100 g C $m^{-2}\cdot yr^{-1}$, mesotrophic 100–300 g C $m^{-2}\cdot yr^{-1}$, eutrophic 300 - 500 g C $m^{-2}\cdot yr^{-1}$, and hypereutrophic > 500 g C $m^{-2}\cdot yr^{-1}$). There are several main factors that must be considered when assessing the TSI and the ecosystem responses to eutrophication, including: 1) nutrient concentrations in the estuary; 2) nutrient sources; 3) export rates (*i.e.*, flushing, microbially-mediated losses through respiration and denitrification); and 4) nutrient recycling/regeneration rates [89]. Management measures needed to mitigate the symptoms and effects of eutrophication should not only focus on nitrogen and phosphorus inputs (primarily inorganic nitrogen and phosphorus as well as organic forms) but also the hydrologic controls of their delivery to an estuary or coastal marine waterbody, and the methods of nutrient reduction to be implemented.

Remediation of environmental impacts in the US typically includes regulations to protect receiving waters and the application of Total Maximum Daily Loads (TMDL) to limit the amount of nutrient inputs to a receiving waterbody. For example, in 2010, the U.S. Environmental Protection Agency (USEPA) set the Total Maximum Daily Load limits on the amount of nitrogen and phosphorus allowed to enter Chesapeake Bay (USA). According to the USEPA [92], a TMDL establishes the maximum amount of a pollutant allowed to enter a waterbody so that the waterbody will meet and continue to meet water quality standards for that particular pollutant. In addition to documenting a pollutant reduction target, it allocates the load reductions necessary to the source(s) of the pollutant to achieve the overall target. A TMDL is considered part of Section 303(d) of the Clean Water Act, which specifies the process for identifying impaired waters and developing plans to restore them.

Eutrophication of estuarine and coastal marine environments increased dramatically after 1970. It remains a serious global environmental concern today as watershed development and poor land-use practices have removed soils and vegetation, creating more impervious land cover that accelerates runoff and delivery of nutrients and organic matter to rivers and streams (**Table 3**). These anthropogenic changes have contributed to widespread and pervasive water quality problems in estuarine and coastal marine waters [6]-[8] [38] [62] [74] [76]. The threat of coastal eutrophication is continuing to increase with climate change [7] [17] [19] [93]-[95]. The amount of reactive nitrogen and phosphorus entering estuarine and other coastal marine waters has increased dramatically over the past several decades with greater use of agricultural fertilizers and fossil fuels, and escalating climate change causing significant ecosystem impacts [87] [96]-[98].

Climate change is an increasingly important factor in eutrophication development in estuarine and coastal marine environments due in part to the greater interaction between atmospheric forcing factors and availability of nutrients [19] [33]. As inferred above, higher precipitation in many regions increases runoff of nutrients from agricultural lands and fertilized lawns, and they stimulate primary production and organic matter accumulation in receiving waters. It also modulates flushing and water residence times. Pulsed freshwater discharges from storms and land runoff strengthen stratification of coastal waterbodies and restrict exchange of surface and bottom waters, resulting in deoxygenation of deeper waters via microbial-mediated decomposition of organic matter.

Climate models predict heavier regional precipitation intensity (up to ~15% - 20% greater) due to climate change, although the regions of elevated precipitation will vary. Frid and Caswell [55] indicated a possible 50% increase in precipitation above 50˚N latitude and up to a 20% decrease between 20˚ and 50˚N and ˚S latitudes. For some of the locations experiencing heavier precipitation and runoff, nutrient overenrichment and excessive organic matter supply will escalate environmental impacts and potentially decrease ecosystem services and reduce goods and benefits (e.g., fish and shellfish production) for human use [18]. More sediments will reach estuarine and coastal marine waters affecting water column turbidity and the benthic habitat. Flushing rates in estuaries will increase as well, while water residence times will decrease. Variable wind patterns can shift salinity regimes, water circulation, and water column mixing, influencing dissolved oxygen levels in deeper waters and organism distribution. Rising sea levels will increase salinization of estuaries, modulating the species composition of biotic communities upestuary.

Higher water temperatures and salinities strengthen pycnoclines and reduce diffusion of oxygen to bottom waters as well as nutrient recycling to surface waters. Reduced wind velocities in some regions can hinder vertical mixing and reoxygenation of oxygen-depleted bottom waters as well as decrease water column nutrient distributions, thereby affecting primary production and food-web dynamics. With elevated organic matter supply and increased respiratory demand for oxygen below the pycnocline, conditions are favorable for hypoxia formation [40]. Additionally, higher temperatures lower oxygen solubility, increase metabolism and mineralization rates, and lead to greater production of organic matter, compounding water quality problems that affect the abundance and distribution of organisms [14] [18] [74]. With less dissolved oxygen transmission to deeper waters and greater microbial decomposition of organic matter in and on bottom sediments, oxygen-depleted bottom waters can spread hypoxic or anoxic conditions over extensive areas, endangering biotic communities and habitats over broad areas [10] [17] [40] [41] [59]. In addition, declining oxygen concentrations affect biogeochemical cycling of nutrients and other substances that affect phytoplankton production and the trophic balance of an ecosystem [17]. Bottom sediments are a sink for nutrient inputs, while benthic-pelagic coupling represents an important link returning nutrients from bottom sediments to the water column, which can exacerbate eutrophication impacts in estuaries [10]. Hypoxia affects ecosystems extending from shallow estuaries through coastal ocean and open ocean waters to depths of 600 - 700 m [40]. These waters include some of the most productive aquatic ecosystems on Earth.

Seasonal and multi-annual hydrologic variability (wet and dry-drought periods—El Niño and La Niña years), higher intensity hurricane activity, nor-easters, and severe summer thunderstorms interact with non-climatic anthropogenic stressors to impact estuarine and coastal marine ecosystem processes [19] [35] [62] [81]. Stronger winds associated with a warmer planet and more extreme intense storms with heavy rainfall create hydrologic complexity with increased water column mixing, altered water circulation patterns, and changing salinity regimes in coastal waters affecting organism abundance, distribution, and trophodynamics [6]. They affect longshore currents and the upwelling systems that deliver nutrients from offshore ocean waters, contributing to nutrient enrichment of nearshore waters [87]. Upwelling of nutrient-rich deep ocean waters into nearshore areas often stimulate massive phytoplankton blooms that can impact fisheries and aquaculture fish farms.

A major concern is the occurrence of HABs which are on the rise in estuaries and coastal marine waters with increasing climate change [19]. HABs include environmentally damaging taxonomic groups (e.g., cyanobacteria, red-tide dinoflagellates, and brown-tide pelagophytes) that impair water quality and pose a threat to shellfish and biotic communities as well as a potential danger to humans consuming contaminated seafood products [14]. High rainfall by tropical cyclones, such as those commonly striking the North Carolina coast (USA), foster nutrient and organic matter loading, increasing primary production, and mediating eutrophication, leading to significant biogeochemical changes along the freshwater to marine continuum [19] [99]. For example, there have been 38 tropical storms striking North Carolina's coastal areas over the past three decades, including Hurricanes Floyd (1999), Matthew (2016), and Florence (2018) that delivered unprecedented amounts of rainfall and flooding waters, causing significant biotic changes in the Albemarle-Pamlico estuarine system [19] [95].

Seitzinger *et al.* [93] noted that nutrient loading effects are not only contingent upon the concentration of nutrients in freshwater discharges but also on the nutrient forms and nutrient ratios that occur. They also observed that anthropogenic loading of dissolved inorganic nutrients (DIN, DIP) to coastal ecosystems is two to three times greater than delivered by natural processes, reflecting the overwhelming influence of human activities on nutrient dynamics and water quality conditions in estuarine and nearshore ocean waters. Coastal areas that have less nutrient management also exhibit the highest nutrient inputs to the coastal zone. Because of the large human coastal population, unmanaged or poorly managed waters in coastal watersheds substantially increase nutrient loading and associated impacts in estuarine and coastal marine waters [100] [101].

Nutrient overenrichment is often most evident in shallow coastal bays, lagoons, and semi-enclosed estuaries with restricted circulation, low flushing rates, and relatively long water residence times that receive nutrients from highly developed coastal watersheds with agricultural activity [19] [83] [102] [103]. Many of these shallow ecosystems are eutrophied with nutrient loading stimulating excessive phytoplankton and benthic macrophyte production leading to elevated autochthonous loads of organic matter and oxygen-depleted bottom waters detrimental to benthic communities with impacts reverberating through upper trophic levels. Hypoxia is often more episodic in the shallower (1 - 5 m) than the deeper coastal waterbodies, fluctuating over time scales of hours to days or even weekly depending on whether the water column is well mixed by wind activity or periodically stratified. In contrast, hypoxia in deeper stratified estuaries and coastal shelf waters (10 - 50 m) can persist over a summer season or longer, such as in Chesapeake Bay and Long Island Sound [10] [40].

In shallow estuaries, eutrophication typically causes a shift in dominance from seagrasses and perennial macroalgae to ephemeral, bloom-forming macroalgae and epiphytes that affect benthic faunal communities [103] [104]. However, eutrophication and hypoxia development in many of these shallow ecosystems are often less well studied than in larger, deeper and more prominent estuarine and coastal marine ecosystems [77]. Bottom habitats typically lie within the photic zone in these shallow ecosystems, which enhances their primary production and promotes eutrophication when nutrient inputs are elevated [13]. Since coastal lagoons occupy about 13% of coastal shorelines worldwide and are highly responsive to nutrient and chemical contaminant inputs, they require the focus of sound and careful management practices for successful environmental and resource sustainability [102].

Coastal wetlands are vulnerable to increasing temperatures, rising sea levels, and nutrient enrichment, and these factors have taken a toll. Rising sea levels are shifting shorelines landward, eroding salt marshes and other coastal wetlands habitat, and endangering their sustainability [65]. Wetlands upland migration in response to sea level rise is obstructed in many areas due to human shoreline defense structures that create coastal squeeze and the loss of wetlands habitat, rendering developed communities in coastal watersheds more vulnerable to storms, flooding, and other hazards. Other direct anthropogenic impacts (e.g., land reclamation and impoundments) have caused destruction of wetlands habitat as well [18].

Gedan *et al.* [105] and Deegan *et al.* [106] found that eutrophication is a driver of structural salt marsh community losses in New England (USA). In experimental work on *Spartina alterniflora* marsh, Deegan *et al.* [106] showed that at nitrogen levels commonly associated with coastal eutrophication there were significant impacts, including creek-bank collapse and conversion of creek-bank marsh to unvegetated mud, indicating excessive nutrient loading impacted the habitat. Reef *et al.* [107] indicated that eutrophication also negatively impacts mangroves. In addition, Lotze *et al.* [15] reported that eutrophication is responsible for increasing fragmentation, depletion, and complete loss of seagrass habitat; Orth *et al.* [108] (2006) and Waycott *et al.* [109] emphasized that eutrophication poses a serious threat to seagrass ecosystems globally. About 25% - 50% of coastal wetlands worldwide have been lost over the past 50 years, mainly due to anthropogenic effects [110]. Since they are vital blue carbon habitats for the sequestration of CO_2, accounting for the storage of nearly 50% of the total organic carbon buried in marine sediments, their losses have been particularly problematic for mitigating climate change effects in coastal ecosystems.

6. Nutrient Limitation

Nitrogen and phosphorus are the most important limiting nutrients to primary production in aquatic ecosystems [76] [111]. Nitrogen is generally the dominant limiting nutrient in most estuarine and coastal marine environments [35] [76] and is mainly responsible for eutrophication development there [10]. Phosphorus is the primary limiting nutrient in freshwater ecosystems as well as some estuaries, such as Apalachicola Bay on the northwest coast of Florida (USA). In addition, some estuarine and coastal marine ecosystems exhibit nitrogen and phosphorus co-limitation [112]. Both nitrogen and phosphorus are important in many brackish water systems such as in the Baltic region [10]. Furthermore, nitrogen or phosphorus limitation of primary production may change temporally and spatially in the same waterbody, with phosphorus typically limiting in the spring and nitrogen limiting in the summer. Low silica levels can limit primary production of marine diatoms. This phytoplankton group can produce extensive spring blooms in temperate estuaries and coastal marine waters. Nutrient availability is an important factor in whether primary production is either nitrogen or phosphorus limited [87]. Because changes in nutrient limitation commonly occur along the freshwater to marine continuum, reduction of both nitrogen and phosphorus loading should be given high priority by management programs tasked with mitigating HABs and other water quality problems that develop [19] [113]. Nutrient concentrations vary considerably in estuarine ecosystems because of multiple nutrient inputs from terrestrial, marine, and atmospheric sources, as well as the flux of biotic uptake, sedimentation, denitrification, mineralization of organic matter, and nutrient transport to offshore waters [14] [16].

Nitrogen and phosphorus availability differs in estuarine and coastal marine environments. For example, much phosphorus entering these environments is sorbed to sediment and organic particles and thus may not be bioavailable. Greater development of coastal watersheds over the past several decades has increased the bioavailability of reactive nitrogen in estuaries. Galloway *et al.* [96] recounted that the largest sources of reactive nitrogen are inorganic nitrogen in fertilizers, NOx emissions from fossil-fuel combustion, and nitrogen fixation in agricultural lands. Howarth and Marino [76], Seitzinger *et al.* [93], Seitzinger and Phillips [94], and Howarth *et al.* [98] stressed that increased use of reactive nitrogen in fertilizers and greater land runoff have been a significant driver of eutrophication occurrence in coastal ecosystems. Since the onset of greater anthropogenic nutrient loading of rivers and estuaries in the 1950s, 1960s and 1970s, eutrophication impacts have become more pervasive and acute, including declining water quality, altered biogeochemical processes and biotic communities, and the loss of vital habitats (e.g., seagrasses, shellfish beds, and coral reefs) [7] [32] [49] [110]. Howarth *et al.* [97] stated that chemical fertilizer use increased dramatically after WWII, being a major contributor to eutrophication development in subsequent years in estuarine and coastal marine waters. Diffuse sources of nutrients from agricultural and urban land areas have become more important than point source inputs for eutrophication and hypoxia development in coastal ecosystems [17] [19] [30] [76] [112] [114].

Howarth *et al.* [98] reported that over nearly a four-decade period (1961 to 1997), the total reactive nitrogen export in rivers to the coastal ocean nearly doubled from 3.0 Tg N yr^{-1} to 5.0 Tg N yr^{-1}. Climate change has also become an increasingly important driver of nutrient pollution in coastal ecosystems [2] [29]. Many U.S. estuaries are moderately to highly eutrophic today due largely to human-mediated activities linked to greater land-use and land-cover modifications in coastal watersheds [6] [14] [82].

The trophodynamics of estuarine and coastal marine ecosystems have been significantly affected by eutrophication in which primary producers respond to bottom-up physical-chemical drivers (nutrients, light, temperature) and top-down controls (grazers and predators), leading to altered food-web structure that affects fishery yields and other ecosystem services [18] [49] [81]. In these ecosystems, characterized by highly variable hydrology, salinity, nutrients, and other factors, the species composition, abundance, diversity, and distribution of organisms often change considerably both spatially and temporally, with massive kills of fish and benthic invertebrates commonly occurring in deoxygenated bottom waters [39] [57] [58]. Nutrient overenrichment, algal bloom formation, and epiphytic overgrowth of vegetation surfaces reduce or block light transmission to submerged aquatic vegetation (e.g., seagrass beds) and, in extreme cases, result in the total dieback of this critically important benthic habitat [6] [8] [85] [86]. The insidious degrading effects of eutrophication and the deleterious impacts of hypoxia can significantly reduce productive commercial and recreational fisheries and decrease human use of these coastal ecosystems [18] [39] [57] [58] [83].

Howarth and Marino [76] estimated that nitrogen fluxes to the U.S. coast alone increased by a sixfold measure compared to previous decades and reached even higher numbers in the North Sea and other coastal waterbodies. Nutrient overenrichment is a primary causative factor for increased (nuisance and toxic) algal blooms and hypoxia development, which can substantially reduce ecosystem services. As noted previously, HABs are hazardous to estuarine and coastal marine organisms, particularly benthic communities adversely affected by shading effects and deoxygenation in deeper waters. For example, *Karenia brevis* is a dinoflagellate that forms red tides and produces a potent toxin (brevetorin) causing fish kills. Humans consuming shellfish contaminated with toxins from red tides can develop paralytic shellfish poisoning, a life-threatening illness that damages nervous, respiratory, and cardiovascular systems. *Aureococcus anophagefferens*, a brown-tide pelagophyte, impairs the growth of shellfish populations (e.g., hard clams, *Mercenaria mercenaria*), reducing their market value.

The prevailing view of coastal scientists today regarding the optimal management of eutrophication in estuarine and coastal marine environments is the dual reduction of nitrogen and phosphorus loadings [35] [87] [112] [114]-[116]. Watershed management strategies employ multiple corrective measures for controlling eutrophication, including adapting low-impact development and best management practices in watersheds, upgrading stormwater controls, advancing open space preservation, enhancing riparian buffers and wetlands habitat, and implementing government regulatory measures to limit nutrient loading (e.g., Total Maximum Daily Loads –TMDLs) [102]. Seitzinger *et al.* [93] stressed the need for a holistic integrated approach to assess trends in river nutrient export by examining the effect of multiple factors (e.g., agricultural nutrient management, sewage treatment, socioeconomic trends, and food consumption). The goal is to improve water quality in freshwater ecosystems upstream of coastal waters, although it is important to manage water quality along the entire freshwater to marine continuum.

Several factors modulate the link between eutrophication and severity of hypoxia (e.g., land runoff, nutrient inputs, water column stratification, primary productivity, and microbial decomposition of organic matter) [17] [62] [81]. These factors are influenced by climate change through increases in temperature, storm activity, precipitation, wind action, sea level rise, acidification, and other variables, which then affect oxygen availability and ecological responses to hypoxia, as observed by Altieri and Gedan [69]. The additive, synergistic, or antagonistic interactions of multiple physical-chemical-biotic factors and climatic drivers that affect hydrologic and nutrient loading complicate the study of eutrophication development in estuarine and coastal marine ecosystems [6] [19]. However, detailed investigations indicate that climate change is facilitating coastal eutrophication and the increase in severity and expansion of hypoxic zones [39] [41] [58] [117] [118].

7. Hypoxia Link

Increasing human population growth along coasts, watershed urbanization, industrialization, and agricultural intensification over the past 50 years have had far-reaching effects on increased nutrient and organic matter loading and hypoxia development in estuarine and coastal marine waters. Dissolved oxygen is a keystone molecule in estuarine and coastal marine environments because of its critical role in the functioning of ecosystem processes, such as the production and decomposition of organic matter and the cycling of inorganic substances [10]. Hypoxia and anoxia develop in estuarine and coastal marine waters when oxygen sinks exceed oxygen sources, being driven by organic matter supply, respiration of the organic matter by microbes and metazoans, and the microbial oxidation of reduced inorganic species (e.g., ammonium and hydrogen sulfide) [119]. Hence, the mineralization of organic matter in and on bottom sediments and the remineralization of nutrients into the water column stimulate additional production of organic matter and the persistence of hypoxia or anoxia, most notably in bottom waters. Warming waters linked to climate change also promote deoxygenation of coastal waters by decreasing the solubility of oxygen in seawater, while concurrently increasing vertical stratification and oxygen consumption [119].

Physical processes play a significant role as well, with larger seasonal increases in the frequency and volume of freshwater inputs contributing to stronger density stratification that hinders vertical mixing of the water column and nutrient loading at depth. Hypoxia is more likely to occur when organic matter supply and transport to bottom waters are high, water residence time is protracted, and water exchange and ventilation are minimal [40]. Areas of hypoxia often underlie highly productive upwelling zones in coastal waters characterized by algal blooms and high accumulation of organic matter in bottom sediments [10] [17]. Increased wind forcing and reduced freshwater inputs occurring at least seasonally typically terminate water column stratification and increase vertical mixing and the resupply of oxygen, subsequently reducing hypoxia/anoxia occurrence.

While excess nutrient enrichment is a primary driver of eutrophication and deoxygenation, physical drivers that limit reaeration of bottom water also play a significant role in hypoxia formation [41]. Warming of bottom waters affects dissolved oxygen levels, particularly in regions where the water column is stratified in summer, such as in Chesapeake Bay [10] and some coastal waters in the UK and elsewhere [120]. Hypoxia reduces habitat availability and can be physiologically challenging or lethal to many estuarine and marine organisms. Greater frequency of extreme events (e.g., storms, floods, and droughts) affects organism responses, as does the generation time of the affected organisms, amounting to hours to days for phytoplankton, months to years for benthos, and years to decades for fish [95].

Depleted dissolved oxygen levels are hazardous to biotic communities, particularly in the benthos where organic matter accumulates and microbial decomposition predominates [41]-[43] [58]. Nutrients regenerated by mineralization in bottom sediments create biogeochemical feedbacks that increase the availability of both nitrogen and phosphorus in the water column that fuels additional phytoplankton and macrophyte production, which can accelerate eutrophication and expansion of hypoxia/anoxia along the seafloor [59] [77] [103] [112]. In contrast, denitrification and anaerobic ammonium oxidation (anammox) in bottom sediments result in a net loss of bioavailable nitrogen via the formation of dinitrogen gas (N_2) [58].

As explained by Howarth *et al.* [77], even moderate increases in nutrient delivery and eutrophication in a highly stratified waterbody can result in hypoxic or anoxic conditions that are detrimental. In these impacted waters, benthic organisms typically exhibit increased mortality, decreased diversity, and altered reproduction, abundance, and distribution. The structure of benthic faunal communities exposed to eutrophic conditions with elevated supply of organic matter in bottom sediments often shift to dominance by pollution tolerant species [42]. Eutrophication is particularly problematic because it can also sustain frequent and intense destructive hypoxic events over extensive areas such as in the northern Gulf of Mexico [17] [43]. Here, high nitrogen loads discharged from the Mississippi River (USA), together with physical dynamics on the continental shelf that support vertical stratification, create conditions for oxygen stress and chronic hypoxia over areas that have exceeded 17,000 km^2 [17] [40] [41] [59]. Other estuarine and coastal marine ecosystems with chronic hypoxia characteristically develop near altered watershed landscapes, where agricultural activity and runoff are intense [10].

The occurrence of oxygen-depleted dead zones has increased greatly in marine waters over the past 75 years, doubling every decade with greater eutrophication and climate change and causing devastating impacts on biotic communities and habitats globally [17] [40] [41] [43] [56] [69]. The effects in coastal waters have been most extreme, with Breitburg *et al.* [58] documenting more than 500 hypoxic sites (oxygen concentrations ≤ 2 mg liter^{-1} (=63 mmol liter^{-1} or $\cong 61$ μmol·kg^{-1}) since 1950. They reported that fewer than 10% of these coastal ecosystems were hypoxic prior to 1950. Between 1995 and 2007 alone, Diaz and Rosenberg [43] identified 405 dead zones affecting a total area of 247,000 km^2. Hypoxic zones in estuarine and marine waters typically expand during the summertime, as is evident in the Chesapeake Bay, northern Gulf of Mexico, Baltic waters, German Bight, Danish coast, and Adriatic Sea.

Increased alteration of coastal wetlands over the past 50 years due to agricultural expansion and urban development, levee construction, modified hydrologic pathways, and escalating climate change have accelerated eutrophication and worsened hypoxia in nearby waters. Similar observations have been made in other coastal ecosystems. For example, Paerl *et al.* [116] showed that eutrophication has been problematic in the San Francisco Bay Delta (USA), where the natural hydrologic system has been significantly altered by channelization, dam construction, freshwater diversions, and levees in conjunction with chronic freshwater withdrawal. While human-altered hydrologic systems are common in coastal regions worldwide, there are few examples of the recovery of heavily impacted estuarine and coastal marine ecosystems from eutrophication and hypoxia that have developed in part from the hydrologic modifications.

The co-occurrence of eutrophication, climate change, and hypoxia poses a threat to the sustainability of estuarine and coastal marine ecosystems [69]. As population growth, watershed development, and human activities expand in coastal regions during the 21st century, efforts by management programs to maintain viable and sustainable estuarine and coastal marine ecosystems will be challenged [10]. Effective management programs are necessary to protect and conserve these vitally important ecosystems.

8. Management Controls

Rabalais *et al.* ([74], p. 1535) concluded more than 15 years ago that "Coastal water quality is currently on the decline." They attributed the observed decline to the effects of escalating human population growth in coastal regions, more intense urbanization and industrialization, expanding agricultural activity, and global climate change, which were increasing eutrophication development as well as the frequency, severity, and extent of hypoxia in estuarine and coastal marine waters. They indicated that greater nutrient loads in these waters due to an array of human activities were an important driver of change and a key link between eutrophication occurrence and hypoxia formation. More specifically, they documented that climatic-driven higher water temperatures, increased nutrient-enriched freshwater flows, and stronger water column stratification were significantly affecting coastal ecosystems around the globe. Since then, additional studies have shown conclusively that, due to a multitude of interactive natural and anthropogenic drivers of change in these environments, it is not reliable to view coastal environmental degradation or management approaches strictly through a singular lens of land-based sources of impacts. In fact, the assessment of coastal environmental conditions and the management strategies necessary to remediate anthropogenic impacts on them are most effective when conducted using a holistic, multidisciplinary integrated approach that couples ecological, physical, and socioeconomic systems for the protection and sustainability of these complex environments [101]. Solutions go beyond scientific intervention to include necessary societal controls or changes in culture [18] [24] [25] [101].

Eutrophication and hypoxia in estuarine and coastal marine waters are among the most serious coastal environmental concerns today. That they are exacerbated by escalating climatic drivers of change raises the concerns to a higher level. These pernicious problems can be mitigated greatly or even reversed by implementing long-term, broad-scale, and persistent efforts to reduce nutrient loads [17]. The reduction of nutrient loading is a key factor in circumventing the damaging effects of eutrophication and globally expanding hypoxia [7] [40].

Climatic drivers of change act on the most extensive temporal and spatial scales relative to other anthropogenic stressors, and the deleterious effects resulting from the multiple interactions of these factors in estuarine and coastal marine ecosystems are challenging to management programs tasked with remediating their ecological impacts [100] [101]. These management programs are in place to ensure that biodiversity is maintained and that the structure and function of the ecosystems are sustainable [26]. While a primary goal of the programs is to maintain coastal ecosystems in a healthy, productive, and resilient state, an additional goal is to concurrently protect delivery of ecosystem services and societal goods and benefits derived from them for human use [6] [18] [21]. This can be achieved most effectively by implementing an ecosystem-based management approach involving the collective application of management programs, governance (*i.e.*, administration, policies, and legislation), and sustainable development plans that rely on an interplay of science, technology, and societal elements. It should consist of an integrated holistic design in which humans are also part of the whole ecosystem being investigated [11] [18] [23] [24] [26]. Recently, Borja *et al.* [22] developed a comprehensive conceptual framework model within an ecosystem-based management approach that advances the knowledge base on the cumulative effects of multiple pressures on estuarine and marine ecosystems and their services and promotes sustainable use of the ecosystems.

Difficulties of managing estuarine and coastal marine environments are ascribed to the complex driver interactions that impact the ecological structure and function of ecosystems, the variable physico-chemical processes therein, and the socio-economic components that must be considered as well [18] [24] [26] [37]. A highly successful management approach that addresses the causes, consequences, and responses to impacts has existed in various forms since the early 1990s. The most recent version is the cyclical DAPSI(W)R(M) framework (*i.e.*, Drivers-Activities-Pressures-State Change-Impact-Responses-Recovery), which integrates relationships between human activities, their pressures and impacts to the environment, and the management responses with solutions to the deleterious effects [18] [24] [71]. Specific elements of this framework include the following: Drivers (human needs, activities, and the economic sectors responsible for the environmental pressures), Pressures (particular stressors on the environment), State (the characteristics and conditions of the environment), Impacts (effects on human welfare due to changes in the natural and human system and the ways in which humans use the estuarine and marine areas), Responses (management measures used and the creation of different policy options and economic instruments to overcome the state changes and impacts), and Recovery (a reduction in the state changes as a result of these actions which may include restoration as an integral component) [18]. Each DAPSI(W)R(M) cycle relates to a particular Driver or human activity in which the management unit is the estuarine or coastal marine ecosystem.

Another useful management strategy for supporting healthy estuarine and coastal marine environments and for sustaining services to society is ecosystem-based marine spatial planning, which informs the spatial distribution of activities in an area [72] [121] [122]. It is a valuable strategic instrument for dealing with conflicting spatial use of marine resources [72]. According to Foley *et al.* ([123], p. 956), an important element of this management strategy is to "maintain the delivery of valuable ecosystem services for future generations in a way that meets ecological, economic, and social objectives." Ecological principles are incorporated into the applications to ensure healthy functioning ecosystems and biodiversity conservation, while also contributing to sustainable economic and societal benefits. Recently, Galparsoro *et al.* [11] developed a useful assessment framework and tool that integrates fundamental principles of an ecosystem approach to management that addresses the implementation challenges of ecosystem-based management principles in marine spatial planning processes. Furthermore, Papadopoulou *et al.* [124] identified 19 tool groups useful for application in the ecosystem-based management context.

Anthropogenic activities cause pressures that are often detrimental to estuarine and coastal marine environments [125]. They are subject to and can contribute to hazards that become risks when something of value to humans is adversely affected [18]. An example is overfishing that causes a decline of fisheries, or the input of contaminants that impairs water quality. This is why socio-economic factors are also important in assessing and managing the condition of estuarine and coastal marine ecosystems.

9. Conclusions

Climate change is a major forcing factor modulating ecosystem processes in estuarine and coastal marine environments. Climate change drivers interact additively, synergistically, or antagonistically with multiple non-climatic anthropogenic stressors to alter physico-chemical conditions and biotic communities in these environments. The impact of climate change on coastal environments has progressively increased since the mid-20th century with rising global mean temperature resulting in the modification of ecosystem structure and function and the loss of ecosystem services of value to humankind. Coastal ecosystems are thus in a state of flux driven by climatic forcings that are causing a paradigm shift in the assessment and management of these vital environments. This article examines the interaction of climate change drivers and eutrophication as an example of how significant the resulting impacts are on estuarine and coastal marine environments. The main conclusions are as follows:

1) Eutrophication is an insidious degrading environmental condition caused by an increase in the rate of organic matter supply to an ecosystem and the development of undesirable consequences that pose a threat to its structure and function. The deleterious impacts of eutrophication are on the rise because of greater anthropogenic alteration of coastal watersheds, accelerated nutrient and organic matter inputs, and climate change.

2) Symptoms of eutrophication include an array of cascading environmental problems such as HABs, impaired water quality, loss of essential habitat (e.g., seagrasses, mangroves, salt marshes, and shellfish beds), reduced biodiversity,

species distributional shifts, altered biotic communities, declining harvestable fisheries, imbalanced trophic food webs, oxygen depletion (hypoxia and anoxia), and diminished ecosystem resilience.

3) In shallow estuaries, eutrophication causes a shift in macrophyte dominance from seagrasses and perennial macroalgae to ephemeral, bloom-forming macroalgae and epiphytes leading to significant changes in biotic communities.

4) Nutrient enrichment and organic matter loading in estuarine and coastal marine environments emerged as an escalating ecological problem after 1950 due to increasing human population growth and development in coastal regions and the greater influence of climate change, which has become more impactful in recent decades driven by higher global mean temperature.

5) Allochthonous and autochthonous inputs of organic matter in estuarine and coastal marine environments are increasing with greater influence of climate change.

6) Anthropogenic climatic forcings, primarily those factors linked to an inability to curb greenhouse gas emissions (notably carbon dioxide, nitrous oxides, and methane), as well as deforestation and watershed land-use and land-cover changes, have increased air and water temperatures and altered biogeochemical cycling and other coastal processes.

7) The interaction of climate change forcings and eutrophication exacerbates adverse effects on the structure and function of estuarine and coastal marine biotic communities.

8) Increased storm intensity and precipitation, land runoff, river discharges, and warming driven by climate change are leading to greater nutrient delivery and organic matter loading, enhanced thermal and salinity stratification, altered water circulation, increased algal blooms, light attenuation in the water column, biogeochemical and trophodynamic changes, and deteriorated sediment and water quality in estuarine and coastal marine ecosystems.

9) The frequency, intensity, and extent of hypoxia are increasing in estuarine and coastal marine environments where climate change amplifies the effects of eutrophication.

10) Hypoxia and anoxia of bottom waters have devastating impacts, often resulting in extensive loss of estuarine and marine life in benthic communities, fisheries declines, as well as damage to habitats.

11) The co-occurrence of climate change, eutrophication, and hypoxia poses a threat to the viability and sustainability of estuarine and coastal marine environments.

12) A primary goal of estuarine and coastal marine management programs is to maintain coastal ecosystems in a healthy, productive, and resilient state, and to protect sustainable delivery of ecosystem services and societal goods and benefits derived from them for human use. To effectively assess and remediate the impacts of eutrophication and climate change for long-term protection and sustainability of these environments, a holistic integrated and unifying management framework

is required to address the causes, consequences, and responses to the impacts. In this respect, the cyclical DAPSI(W)R(M) framework (*i.e.*, Drivers-Activities-Pressures-State Change-Impact-Responses-Recovery) is a highly successful management approach that has existed since the early 1990s. It integrates relationships between human activities, their pressures and impacts on the environment, and the management responses with solutions to the deleterious effects.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Doney, S.C., Ruckelshaus, M., Emmett Duffy, J., Barry, J.P., Chan, F., English, C.A., *et al.* (2012) Climate Change Impacts on Marine Ecosystems. *Annual Review of Marine Science*, **4**, 11-37. https://doi.org/10.1146/annurev-marine-041911-111611

[2] Statham, P.J. (2012) Nutrients in Estuaries—An Overview and the Potential Impacts of Climate Change. *Science of the Total Environment*, **434**, 213-227. https://doi.org/10.1016/j.scitotenv.2011.09.088

[3] Robins, P.E., Skov, M.W., Lewis, M.J., Giménez, L., Davies, A.G., Malham, S.K., *et al.* (2016) Impact of Climate Change on UK Estuaries: A Review of Past Trends and Potential Projections. *Estuarine*, *Coastal and Shelf Science*, **169**, 119-135. https://doi.org/10.1016/j.ecss.2015.12.016

[4] Simeoni, C., Furlan, E., Pham, H.V., Critto, A., de Juan, S., Trégarot, E., *et al.* (2023) Evaluating the Combined Effect of Climate and Anthropogenic Stressors on Marine Coastal Ecosystems: Insights from a Systematic Review of Cumulative Impact Assessment Approaches. *Science of the Total Environment*, **861**, Article ID: 160687. https://doi.org/10.1016/j.scitotenv.2022.160687

[5] Day, J.W., Rybczyk, J.M., Mann, M.E., and Stephens, J.R. (2024) Climate Change: Effects, Causes, Consequences, Physical Hydromorphological, Ecophysiological, and Biogeochemical Changes in Coastal Wetlands and Waters. In: Kennish, M.J. and Elliott, M., Eds., *Anthropogenic Uses*, *Effects*, *and Solutions on Estuarine and Coastal Systems*, *Vol.* 6, *Treatise on Estuarine and Coastal Science*, 2*nd Edition*, Elsevier, 626-641.

[6] Kennish, M.J. (2024) Anthropogenic Drivers of Estuarine Change. In: Kennish, M.J., Paerl, H.W., and Crosswell, J.R., Eds., *Climate Change and Estuaries*, CRC Press, 75-98. https://doi.org/10.1201/9781003126096

[7] Kennish, M.J. (2024) Nutrient Inputs and Organic Carbon Enrichment: Causes and Consequences of Eutrophication. *Treatise on Estuarine and Coastal Science* (*Second Edition*), **6**, 218-258. https://doi.org/10.1016/b978-0-323-90798-9.00015-9

[8] Kennish, M.J., Paerl, H.W., and Crosswell, J.R. (2024) Introduction to Climate Change and Estuaries. In: Kennish, M.J., Paerl, H.W., and Crosswell, J.R., Eds., *Climate Change and Estuaries*, CRC Press, 3-22. https://doi.org/10.1201/9781003126096

[9] Kennish, M., Paerl, H., Crosswell, J. and Moore, K. (2024) Estuaries Face a Stormy Future. *American Scientist*, **112**, 302-309. https://doi.org/10.1511/2024.112.5.302

[10] Testa, J.M., Carstensen, J., Laurent, A. and Li, M. (2023) Hypoxia and Climate Change in Estuaries. In: Kennish, M.J., Paerl, H.W. and Crosswell, J.R., Eds., *Climate Change and Estuaries*, CRC Press, 143-170. https://doi.org/10.1201/9781003126096-9

[11] Galparsoro, I., Montero, N., Mandiola, G., Menchaca, I., Borja, Á., Flannery, W., *et al.* (2025) Assessment Tool Addresses Implementation Challenges of Ecosystem-Based Management Principles in Marine Spatial Planning Processes. *Communications Earth & Environment*, **6**, Article No. 55. https://doi.org/10.1038/s43247-024-01975-7

[12] Kennish, M.J. (2002) Environmental Threats and Environmental Future of Estuaries. *Environmental Conservation*, **29**, 78-107. https://doi.org/10.1017/s0376892902000061

[13] Kennish, M.J., Brush, M.J. and Moore, K.A. (2014) Drivers of Change in Shallow Coastal Photic Systems: An Introduction to a Special Issue. *Estuaries and Coasts*, **37**, 3-19. https://doi.org/10.1007/s12237-014-9779-4

[14] Kennish, M.J. (2019) Practical Handbook of Marine Science. 4th Edition, CRC Press.

[15] Lotze, H.K., Lenihan, H.S., Bourque, B.J., Bradbury, R.H., Cooke, R.G., Kay, M.C., *et al.* (2006) Depletion, Degradation, and Recovery Potential of Estuaries and Coastal Seas. *Science*, **312**, 1806-1809. https://doi.org/10.1126/science.1128035

[16] Day Jr., J.W., Kemp, W.M., Yáñez-Arancibia, A.Y. and Crump, B.C. (2012) Estuarine Ecology. 2nd Edition, Wiley-Blackwell.

[17] Rabalais, N., Cai, W., Carstensen, J., Conley, D., Fry, B., Hu, X., *et al.* (2014) Eutrophication-driven Deoxygenation in the Coastal Ocean. *Oceanography*, **27**, 172-183. https://doi.org/10.5670/oceanog.2014.21

[18] Elliott, M. and Kennish, M.J. (2024) A Synthesis of Anthropogenic Impacts and Solutions in Estuarine and Coastal Environments. *Treatise on Estuarine and Coastal Science* (*Second Edition*), **6**, 1-56. https://doi.org/10.1016/b978-0-323-90798-9.00126-8

[19] Paerl, H.W. (2024) Climate Change, Phytoplankton, and HABs. In: Kennish, M.J., Paerl, H.W. and Crosswell, J.R., Eds., *Climate Change and Estuaries*, CRC Press, 315-334. https://doi.org/10.1201/9781003126096

[20] Crain, C.M., Kroeker, K. and Halpern, B.S. (2008) Interactive and Cumulative Effects of Multiple Human Stressors in Marine Systems. *Ecology Letters*, **11**, 1304-1315. https://doi.org/10.1111/j.1461-0248.2008.01253.x

[21] Lonsdale, J., Nicholson, R., Judd, A., Elliott, M. and Clarke, C. (2020) A Novel Approach for Cumulative Impacts Assessment for Marine Spatial Planning. *Environmental Science & Policy*, **106**, 125-135. https://doi.org/10.1016/j.envsci.2020.01.011

[22] Borja, A., Elliott, M., Teixeira, H., Stelzenmüller, V., Katsanevakis, S., Coll, M., *et al.* (2024) Addressing the Cumulative Impacts of Multiple Human Pressures in Marine Systems, for the Sustainable Use of the Seas. *Frontiers in Ocean Sustainability*, **1**, Article 1308125. https://doi.org/10.3389/focsu.2023.1308125

[23] Pittman, J. and Armitage, D. (2016) Governance across the Land-Sea Interface: A Systematic Review. *Environmental Science & Policy*, **64**, 9-17. https://doi.org/10.1016/j.envsci.2016.05.022

[24] Elliott, M., Burdon, D., Atkins, J.P., Borja, A., Cormier, R., de Jonge, V.N., *et al.* (2017) "And DPSIR Begat DAPSI(W)R(M)!"—A Unifying Framework for Marine Environmental Management. *Marine Pollution Bulletin*, **118**, 27-40. https://doi.org/10.1016/j.marpolbul.2017.03.049

[25] Elliott, M., Borja, Á. and Cormier, R. (2020) Managing Marine Resources Sustainably: A Proposed Integrated Systems Analysis Approach. *Ocean & Coastal Management*, **197**, Article ID: 105315. https://doi.org/10.1016/j.ocecoaman.2020.105315

[26] Elliott, M., Borja, Á. and Cormier, R. (2023) Managing Marine Resources Sustainably—Ecological, Societal and Governance Connectivity, Coherence and Equivalence in Complex Marine Transboundary Regions. *Ocean & Coastal Management*, **245**, Article ID: 106875. https://doi.org/10.1016/j.ocecoaman.2023.106875

[27] Cronin, T.M. (2016) Climate Change. In: Kennish, M.J., Ed., *Encyclopedia of Estuaries*, Springer, 122-128. https://doi.org/10.1007/978-94-017-8801-4

[28] Intergovernmental Panel on Climate Change (IPCC) (2021) Climate Change 2021: The Physical Science Basis. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., *et al.*, Eds., *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press. https://doi.org/10.1017/9781009157896

[29] He, Q. and Silliman, B.R. (2019) Climate Change, Human Impacts, and Coastal Ecosystems in the Anthropocene. *Current Biology*, **29**, R1021-R1035. https://doi.org/10.1016/j.cub.2019.08.042

[30] Cloern, J. (2001) Our Evolving Conceptual Model of the Coastal Eutrophication Problem. *Marine Ecology Progress Series*, **210**, 223-253. https://doi.org/10.3354/meps210223

[31] Cloern, J.E., Abreu, P.C., Carstensen, J., Chauvaud, L., Elmgren, R., Grall, J., *et al.* (2015) Human Activities and Climate Variability Drive Fast-Paced Change across the World's Estuarine-Coastal Ecosystems. *Global Change Biology*, **22**, 513-529. https://doi.org/10.1111/gcb.13059

[32] Kennish, M.J. (2015) Eutrophication. In: Kennish, M.J., Ed., *Encyclopedia of Earth Sciences Series*, Springer, 304-311. https://doi.org/10.1007/978-94-017-8801-4_2

[33] Paerl, H.W., Valdes-Weaver, L.M., Joyner, A.R. and Winkelmann, V. (2007) Phytoplankton Indicators of Ecological Change in the Eutrophying Pamlico Sound System, North Carolina. *Ecological Applications*, **17**, S88-S101. https://doi.org/10.1890/05-0840.1

[34] Paerl, H.W. and Huisman, J. (2009) Climate Change: A Catalyst for Global Expansion of Harmful Cyanobacterial Blooms. *Environmental Microbiology Reports*, **1**, 27-37. https://doi.org/10.1111/j.1758-2229.2008.00004.x

[35] Paerl, H.W., Crosswell, J.R., Van Dam, B., Hall, N.S., Rossignol, K.L., Osburn, C.L., *et al.* (2018) Two Decades of Tropical Cyclone Impacts on North Carolina's Estuarine Carbon, Nutrient and Phytoplankton Dynamics: Implications for Biogeochemical Cycling and Water Quality in a Stormier World. *Biogeochemistry*, **141**, 307-332. https://doi.org/10.1007/s10533-018-0438-x

[36] Piggott, J.J., Townsend, C.R. and Matthaei, C.D. (2015) Reconceptualizing Synergism and Antagonism among Multiple Stressors. *Ecology and Evolution*, **5**, 1538-1547. https://doi.org/10.1002/ece3.1465

[37] Cabral, H., Fonseca, V., Sousa, T. and Costa Leal, M. (2019) Synergistic Effects of Climate Change and Marine Pollution: An Overlooked Interaction in Coastal and Estuarine Areas. *International Journal of Environmental Research and Public Health*, **16**, Article 2737. https://doi.org/10.3390/ijerph16152737

[38] Turner, R.E. and Rabalais, N.N. (1994) Coastal Eutrophication Near the Mississippi River Delta. *Nature*, **368**, 619-621. https://doi.org/10.1038/368619a0

[39] Breitburg, D.L., Hondorp, D.W., Davias, L.A. and Diaz, R.J. (2009) Hypoxia, Nitro-

gen, and Fisheries: Integrating Effects across Local and Global Landscapes. *Annual Review of Marine Science*, **1**, 329-349. https://doi.org/10.1146/annurev.marine.010908.163754

[40] Rabalais, N.N., Díaz, R.J., Levin, L.A., Turner, R.E., Gilbert, D. and Zhang, J. (2010) Dynamics and Distribution of Natural and Human-Caused Hypoxia. *Biogeosciences*, **7**, 585-619. https://doi.org/10.5194/bg-7-585-2010

[41] Diaz, R.J. (2015) Anoxia, Hypoxia, and Dead Zones. In: Kennish, M.J., Ed., *Encyclopedia of Earth Sciences Series*, Springer, 19-29. https://doi.org/10.1007/978-94-017-8801-4_82

[42] Diaz, R.J. and Rosenberg, R. (1995) Marine Benthic Hypoxia: A Review of Its Ecological Effects and the Behavioral Responses of Benthic Macrofauna. *Oceanography and Marine Biology Annual Review*, **33**, 245-303.

[43] Diaz, R.J. and Rosenberg, R. (2008) Spreading Dead Zones and Consequences for Marine Ecosystems. *Science*, **321**, 926-929. https://doi.org/10.1126/science.1156401

[44] Levin, L.A., Mendoza, G.F., Neira, C., Giddings, S.N. and Crooks, J.A. (2022) Consequences of Mouth Closure and Hypoxia-Induced State Changes in Low-Inflow Estuaries: Benthic Community and Trait-Based Response. *Estuaries and Coasts*, **46**, 2128-2147. https://doi.org/10.1007/s12237-022-01132-3

[45] Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I., *et al.* (2018) Impacts of 1.5˚C Global Warming on Natural and Human Systems. In: Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., *et al.*, Eds., *Global Warming of* 1.5°C: *IPCC Special Report on Impacts of Global Warming of* 1.5°C *above Pre-Industrial Levels in Context of Strengthening Response to Climate Change*, *Sustainable Development*, *and Efforts to Eradicate Poverty*, Cambridge University Press, 175-312. https://doi.org/10.1017/9781009157940.005

[46] Bindoff, N.L., Cheung, W.W.L., Kairo, J.G., Arístegui, J., Guinder, V.A., Hallberg, R., *et al.* (2022) Changing Ocean, Marine Ecosystems, and Dependent Communities. In: Pörtner, H.O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E.S., *et al.*, Eds., *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, Cambridge University Press, 447-587. https://doi.org/10.1017/9781009157964.007

[47] Wernberg, T., Thomsen, M.S., Baum, J.K., Bishop, M.J., Bruno, J.F., Coleman, M.A., *et al.* (2024) Impacts of Climate Change on Marine Foundation Species. *Annual Review of Marine Science*, **16**, 247-282. https://doi.org/10.1146/annurev-marine-042023-093037

[48] Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., *et al.*, Eds. (2022) Climate Change 2022: Impacts, Adaptation, and Vulnerability. Cambridge University Press, 3056. https://doi.org/10.1017/9781009325844

[49] Wong, P.P., Losada, I.J., Gattuso, J.P., Hinkel, J., Khattabi, A., McInnes, K.L., *et al.* (2014) Coastal Systems and Low-Lying Areas. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., *et al.*, Eds., *Climate Change* 2014: *Impacts*, *Adaptation*, *and Vulnerability*. *Part A*: *Global and Sectoral Aspects*, Cambridge University Press, 361-410. https://doi.org/10.1017/CBO9781107415379.010

[50] Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tigor, M. and Poloczanska, E. (2019) IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Cambridge University Press.

[51] Gulev, S.K., Thorne, P.W., Ahn, J., Dentener, F.J., Domingues, C.M., Gerland, S., *et al.* (2021) Changing State of the Climate System. In: Masson-Delmotte, V., Zhai, P.,

Pirani, A., Connors, S.L., Péan, C., Berger, S., *et al.*, Eds., *Chapter* 2, *Climate Change* 2021: *The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 287-422. https://doi.org/10.1017/9781009157896.004

[52] Fox-Kemper, B., Hewitt, H.T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S.S., Edwards, T.L., *et al.* (2021) Ocean, Cryosphere and Sea Level Change. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., *et al.*, Eds., *Chapter* 9, *Climate Change* 2021: *The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 1211-1362. https://doi.org/10.1017/9781009157896.011

[53] Lima, F.P. and Wethey, D.S. (2012) Three Decades of High-Resolution Coastal Sea Surface Temperatures Reveal More than Warming. *Nature Communications*, **3**, Article No. 704. https://doi.org/10.1038/ncomms1713

[54] Poloczanska, E.S., Burrows, M.T., Brown, C.J., García Molinos, J., Halpern, B.S., Hoegh-Guldberg, O., *et al.* (2016) Responses of Marine Organisms to Climate Change across Oceans. *Frontiers in Marine Science*, **3**, Article 62. https://doi.org/10.3389/fmars.2016.00062

[55] Frid, C.L.J. and Caswell, B.A. (2017) Marine Pollution. Oxford University Press. https://doi.org/10.1093/oso/9780198726289.001.0001

[56] Diaz, R.J. (2001) Overview of Hypoxia around the World. *Journal of Environmental Quality*, **30**, 275-281. https://doi.org/10.2134/jeq2001.302275x

[57] Breitburg, D. (2002) Effects of Hypoxia, and the Balance between Hypoxia and Enrichment, on Coastal Fishes and Fisheries. *Estuaries*, **25**, 767-781. https://doi.org/10.1007/bf02804904

[58] Breitburg, D., Levin, L.A., Oschlies, A., Grégoire, M., Chavez, F.P., Conley, D.J., *et al.* (2018) Declining Oxygen in the Global Ocean and Coastal Waters. *Science*, **359**, eaam7240. https://doi.org/10.1126/science.aam7240

[59] Rabalais, N.N., Turner, R.E., Gupta, B.K.S., Platon, E. and Parsons, M.L. (2007) Sediments Tell the History of Eutrophication and Hypoxia in the Northern Gulf of Mexico. *Ecological Applications*, **17**, S129-S143. https://doi.org/10.1890/06-0644.1

[60] U.S. Environmental Protection Agency (2024) Climate Change Indicators in the United States, 5th Edition. EPA 430-R-24-003. https://www.epa.gov/climate-indicators

[61] Church, J.A., Woodworth, P.L., Aarup, T., and Wilson, W.S. (2010) Understanding Sea Level Rise and Variability. Wiley-Blackwell. https://doi.org/10.1002/9781444323276

[62] Paerl, H.W., Hall, N.S., Hounshell, A.G., Rossignol, K.L., Barnard, M.A., Luettich, R.A., *et al.* (2020) Recent Increases of Rainfall and Flooding from Tropical Cyclones (TCS) in North Carolina (USA): Implications for Organic Matter and Nutrient Cycling in Coastal Watersheds. *Biogeochemistry*, **150**, 197-216. https://doi.org/10.1007/s10533-020-00693-4

[63] Medina, M., Beck, M.W., Hecker, J., Iadevaia, N., Moody, B., Anastasiou, C., *et al.* (2025) Water Quality Trends and Eutrophication Indicators in a Large Subtropical Estuary: A Case Study of the Greater Charlotte Harbor System in Southwest Florida. *Estuaries and Coasts*, **48**, Article No. 56. https://doi.org/10.1007/s12237-025-01488-2

[64] Deegan, L.A., Bowen, J.L., Drake, D., Fleeger, J.W., Friedrichs, C.T., Galván, K.A., *et al.* (2007) Susceptibility of Salt Marshes to Nutrient Enrichment and Predator Removal. *Ecological Applications*, **17**, S42-S63. https://doi.org/10.1890/06-0452.1

[65] Weis, J.S. and Windham-Myers, L. (2024) Environmental Disturbances and Restora-

tion of Salt Marshes. In: Kennish, M. J. and Elliott, M., Eds., *Anthropogenic Uses, Effects, and Solutions on Estuarine and Coastal Systems*, *Volume* 6, *Treatise on Estuarine and Coastal Science*, 2*nd Edition*, Elsevier, 549-595.

[66] Justić, D., Rabalais, N.N. and Turner, R.E. (2005) Coupling between Climate Variability and Coastal Eutrophication: Evidence and Outlook for the Northern Gulf of Mexico. *Journal of Sea Research*, **54**, 25-35. https://doi.org/10.1016/j.seares.2005.02.008

[67] Howarth, R., Swaney, D., Billen, G., Garnier, J., Hong, B., Humborg, C., *et al.* (2011) Nitrogen Fluxes from the Landscape Are Controlled by Net Anthropogenic Nitrogen Inputs and by Climate. *Frontiers in Ecology and the Environment*, **10**, 37-43. https://doi.org/10.1890/100178

[68] Macías-Tapia, A., Mulholland, M.R., Selden, C.R., Clayton, S., Bernhardt, P.W. and Allen, T.R. (2024) Tidal Flooding Contributes to Eutrophication: Constraining Nonpoint Source Inputs to an Urban Estuary Using a Data-Driven Statistical Model. *Estuaries and Coasts*, **48**, Article No. 36. https://doi.org/10.1007/s12237-024-01473-1

[69] Altieri, A.H. and Gedan, K.B. (2014) Climate Change and Dead Zones. *Global Change Biology*, **21**, 1395-1406. https://doi.org/10.1111/gcb.12754

[70] Sinha, E., Michalak, A.M. and Balaji, V. (2017) Eutrophication Will Increase during the 21st Century as a Result of Precipitation Changes. *Science*, **357**, 405-408. https://doi.org/10.1126/science.aan2409

[71] Patrício, J., Elliott, M., Mazik, K., Papadopoulou, K. and Smith, C.J. (2016) DPSIR—Two Decades of Trying to Develop a Unifying Framework for Marine Environmental Management? *Frontiers in Marine Science*, **3**, Article 177. https://doi.org/10.3389/fmars.2016.00177

[72] Hammar, L., Molander, S., Pålsson, J., Schmidtbauer Crona, J., Carneiro, G., Johansson, T., *et al.* (2020) Cumulative Impact Assessment for Ecosystem-Based Marine Spatial Planning. *Science of the Total Environment*, **734**, Article ID: 139024. https://doi.org/10.1016/j.scitotenv.2020.139024

[73] Cormier, R., Elliott, M. and Borja, Á. (2022) Managing Marine Resources Sustainably—The 'Management Response-Footprint Pyramid' Covering Policy, Plans and Technical Measures. *Frontiers in Marine Science*, **9**, Article 869992. https://doi.org/10.3389/fmars.2022.869992

[74] Rabalais, N.N., Turner, R.E., Díaz, R.J. and Justić, D. (2009) Global Change and Eutrophication of Coastal Waters. *ICES Journal of Marine Science*, **66**, 1528-1537. https://doi.org/10.1093/icesjms/fsp047

[75] Boesch, D.F. (2002) Challenges and Opportunities for Science in Reducing Nutrient Over-Enrichment of Coastal Ecosystems. *Estuaries*, **25**, 886-900. https://doi.org/10.1007/bf02804914

[76] Howarth, R.W. and Marino, R. (2006) Nitrogen as the Limiting Nutrient for Eutrophication in Coastal Marine Ecosystems: Evolving Views over Three Decades. *Limnology and Oceanography*, **51**, 364-376. https://doi.org/10.4319/lo.2006.51.1_part_2.0364

[77] Howarth, R., Chan, F., Conley, D.J., Garnier, J., Doney, S.C., Marino, R., *et al.* (2011) Coupled Biogeochemical Cycles: Eutrophication and Hypoxia in Temperate Estuaries and Coastal Marine Ecosystems. *Frontiers in Ecology and the Environment*, **9**, 18-26. https://doi.org/10.1890/100008

[78] Nixon, S.W. (1995) Coastal Marine Eutrophication: A Definition, Social Causes, and Future Concerns. *Ophelia*, **41**, 199-219. https://doi.org/10.1080/00785236.1995.10422044

[79] Nixon, S.W. (2009) Eutrophication and the Macroscope. *Hydrobiologia*, **629**, 5-19. https://doi.org/10.1007/s10750-009-9759-z

[80] Tett, P., Gowen, R., Painting, S., Elliott, M., Forster, R., Mills, D., *et al.* (2013) Framework for Understanding Marine Ecosystem Health. *Marine Ecology Progress Series*, **494**, 1-27. https://doi.org/10.3354/meps10539

[81] Paerl, H.W., Valdes, L.M., Peierls, B.L., Adolf, J.E. and Harding, L.J.W. (2006) Anthropogenic and Climatic Influences on the Eutrophication of Large Estuarine Ecosystems. *Limnology and Oceanography*, **51**, 448-462. https://doi.org/10.4319/lo.2006.51.1_part_2.0448

[82] Kennish, M.J. and Townsend, A.R. (2007) Nutrient Enrichment and Estuarine Eutrophication. *Ecological Applications*, **17**, S1-S2. https://doi.org/10.1890/06-1623.1

[83] Kennish, M.J., Bricker, S.B., Dennison, W.C., Glibert, P.M., Livingston, R.J., Moore, K.A., *et al.* (2007) Barnegat Bay-Little Egg Harbor Estuary: Case Study of a Highly Eutrophic Coastal Bay System. *Ecological Applications*, **17**, S3-S16. https://doi.org/10.1890/05-0800.1

[84] Burkholder, J.M., Tomasko, D.A. and Touchette, B.W. (2007) Seagrasses and Eutrophication. *Journal of Experimental Marine Biology and Ecology*, **350**, 46-72. https://doi.org/10.1016/j.jembe.2007.06.024

[85] Kennish, M., Haag, S. and Sakowicz, G. (2010) Seagrass Decline in New Jersey Coastal Lagoons: A Response to Increasing Eutrophication. In: Kennish, M.J. and Paerl, H.W., Eds., *Coastal Lagoons: Critical Habitats of Environmental Change*, CRC Press, 167-201. https://doi.org/10.1201/ebk1420088304-c8

[86] Moore, K., Shields, E., Parrish, D. and Orth, R. (2012) Eelgrass Survival in Two Contrasting Systems: Role of Turbidity and Summer Water Temperatures. *Marine Ecology Progress Series*, **448**, 247-258. https://doi.org/10.3354/meps09578

[87] Howarth, R.W., Chan, F., Swaney, D.P., Marino, R.M. and Hayn, M. (2021) Role of External Inputs of Nutrients to Aquatic Ecosystems in Determining Prevalence of Nitrogen Vs. Phosphorus Limitation of Net Primary Productivity. *Biogeochemistry*, **154**, 293-306. https://doi.org/10.1007/s10533-021-00765-z

[88] Rocha, C., Ibánhez, J.S.P. and Jiang, S. (2024) Groundwater Quality Restoration and Ecosystem Productivity. In: Kennish, M. J. and Elliott, M., Eds., *Anthropogenic Uses, Effects, and Solutions on Estuarine and Coastal Systems, Volume* 6, *Treatise on Estuarine and Coastal Science*, 2*nd Edition*, Elsevier, 716-736.

[89] Pinckney, J.L., Paerl, H.W., Tester, P. and Richardson, T.L. (2001) The Role of Nutrient Loading and Eutrophication in Estuarine Ecology. *Environmental Health Perspectives*, **109**, 699-706. https://doi.org/10.1289/ehp.01109s5699

[90] Howarth, R.W., Swaney, D.P., Butler, T.J. and Marino, R. (2000) Rapid Communication: Climatic Control on Eutrophication of the Hudson River Estuary. *Ecosystems*, **3**, 210-215. https://doi.org/10.1007/s100210000020

[91] Struyf, E., Van Damme, S. and Meire, P. (2004) Possible Effects of Climate Change on Estuarine Nutrient Fluxes: A Case Study in the Highly Nutrified Schelde Estuary (Belgium, the Netherlands). *Estuarine, Coastal and Shelf Science*, **60**, 649-661. https://doi.org/10.1016/j.ecss.2004.03.004

[92] U.S. Environmental Protection Agency (2025) Overview of Total Maximum Daily Loads (TMDLs). https://www.epa.gov/tmdl/overview-total-maximum-daily-loads-tmdls

[93] Seitzinger, S.P., Mayorga, E., Bouwman, A.F., Kroeze, C., Beusen, A.H.W., Billen, G., *et al.* (2010) Global River Nutrient Export: A Scenario Analysis of Past and Future

Trends. *Global Biogeochemical Cycles*, **24**, GB003587. https://doi.org/10.1029/2009gb003587

[94] Seitzinger, S.P. and Phillips, L. (2017) Nitrogen Stewardship in the Anthropocene. *Science*, **357**, 350-351. https://doi.org/10.1126/science.aao0812

[95] Paerl, H., Christian, R., Bales, J., Peierls, B., Hall, N., Joyner, A., *et al.* (2010) Assessing the Response of the Pamlico Sound, North Carolina, USA to Human and Climatic Disturbances: Management Implications. In: Kennish, M.J. and Paerl, H.W., Eds., *Coastal Lagoons: Critical Habitats of Environmental Change*, CRC Press, 17-42. https://doi.org/10.1201/ebk1420088304-c2

[96] Galloway, J.N., Cowling, E.B., Seitzinger, S.P. and Socolow, R.H. (2002) Reactive Nitrogen: Too Much of a Good Thing? *AMBIO: A Journal of the Human Environment*, **31**, 60-63. https://doi.org/10.1579/0044-7447-31.2.60

[97] Howarth, R.W., Sharpley, A. and Walker, D. (2002) Sources of Nutrient Pollution to Coastal Waters in the United States: Implications for Achieving Coastal Water Quality Goals. *Estuaries*, **25**, 656-676. https://doi.org/10.1007/bf02804898

[98] Howarth, R.W., Boyer, E.W., Pabich, W.J. and Galloway, J.N. (2002) Nitrogen Use in the United States from 1961–2000 and Potential Future Trends. *AMBIO: A Journal of the Human Environment*, **31**, 88-96. https://doi.org/10.1579/0044-7447-31.2.88

[99] Paerl, H.W., Otten, T.G. and Kudela, R. (2018) Mitigating the Expansion of Harmful Algal Blooms across the Freshwater-To-Marine Continuum. *Environmental Science & Technology*, **52**, 5519-5529. https://doi.org/10.1021/acs.est.7b05950

[100] Kennish, M.J. (2021) Drivers of Change in Estuarine and Coastal Marine Environments: An Overview. *Open Journal of Ecology*, **11**, 224-239. https://doi.org/10.4236/oje.2021.113017

[101] Kennish, M.J. (2022) Management Strategies to Mitigate Anthropogenic Impacts in Estuarine and Coastal Marine Environments: A Review. *Open Journal of Ecology*, **12**, 667-688. https://doi.org/10.4236/oje.2022.1210038

[102] Kennish, M. and Paerl, H. (2010) Coastal Lagoons: Critical Habitats of Environmental Change. In: Kennish, M.J. and Paerl, H.W., Eds., *Coastal Lagoons: Critical Habitats of Environmental Change*, 1-15. https://doi.org/10.1201/ebk1420088304-c1

[103] McGlathery, K., Sundbäck, K. and Anderson, I. (2007) Eutrophication in Shallow Coastal Bays and Lagoons: The Role of Plants in the Coastal Filter. *Marine Ecology Progress Series*, **348**, 1-18. https://doi.org/10.3354/meps07132

[104] Kennish, M.J. (2009) Eutrophication of Mid-Atlantic Coastal Bays. B*ulletin of the New Jersey Academy of Science*, **54**, 5-12.

[105] Gedan, K., Altieri, A. and Bertness, M. (2011) Uncertain Future of New England Salt Marshes. *Marine Ecology Progress Series*, **434**, 229-237. https://doi.org/10.3354/meps09084

[106] Deegan, L.A., Johnson, D.S., Warren, R.S., Peterson, B.J., Fleeger, J.W., Fagherazzi, S., *et al.* (2012) Coastal Eutrophication as a Driver of Salt Marsh Loss. *Nature*, **490**, 388-392. https://doi.org/10.1038/nature11533

[107] Reef, R., Feller, I.C. and Lovelock, C.E. (2010) Nutrition of Mangroves. *Tree Physiology*, **30**, 1148-1160. https://doi.org/10.1093/treephys/tpq048

[108] Orth, R.J., Carruthers, T.J.B., Dennison, W.C., Duarte, C.M., Fourqurean, J.W., Heck, K.L., *et al.* (2006) A Global Crisis for Seagrass Ecosystems. *BioScience*, **56**, 987-996. https://doi.org/10.1641/0006-3568(2006)56[987:agcfse]2.0.co;2

[109] Waycott, M., Duarte, C.M., Carruthers, T.J.B., Orth, R.J., Dennison, W.C., Olyarnik, S., *et al.* (2009) Accelerating Loss of Seagrasses across the Globe Threatens Coastal

Ecosystems. *Proceedings of the National Academy of Sciences of the United States of America*, **106**, 12377-12381. https://doi.org/10.1073/pnas.0905620106

[110] Duarte, C.M., Losada, I.J., Hendriks, I.E., Mazarrasa, I. and Marbà, N. (2013) The Role of Coastal Plant Communities for Climate Change Mitigation and Adaptation. *Nature Climate Change*, **3**, 961-968.

[111] Fennel, K. and Laurent, A. (2018) N and P as Ultimate and Proximate Limiting Nutrients in the Northern Gulf of Mexico: Implications for Hypoxia Reduction Strategies. *Biogeosciences*, **15**, 3121-3131. https://doi.org/10.5194/bg-15-3121-2018

[112] Conley, D.J., Paerl, H.W., Howarth, R.W., Boesch, D.F., Seitzinger, S.P., Havens, K.E., *et al.* (2009) Controlling Eutrophication: Nitrogen and Phosphorus. *Science*, **323**, 1014-1015. https://doi.org/10.1126/science.1167755

[113] Paerl, H.W., Scott, J.T., McCarthy, M.J., Newell, S.E., Gardner, W.S., Havens, K.E., *et al.* (2016) It Takes Two to Tango: When and Where Dual Nutrient (N & P) Reductions Are Needed to Protect Lakes and Downstream Ecosystems. *Environmental Science & Technology*, **50**, 10805-10813. https://doi.org/10.1021/acs.est.6b02575

[114] Paerl, H.W., Gardner, W.S., Havens, K.E., Joyner, A.R., McCarthy, M.J., Newell, S.E., *et al.* (2016) Mitigating Cyanobacterial Harmful Algal Blooms in Aquatic Ecosystems Impacted by Climate Change and Anthropogenic Nutrients. *Harmful Algae*, **54**, 213-222. https://doi.org/10.1016/j.hal.2015.09.009

[115] Lewis, W.M., Wurtsbaugh, W.A. and Paerl, H.W. (2011) Rationale for Control of Anthropogenic Nitrogen and Phosphorus to Reduce Eutrophication of Inland Waters. *Environmental Science & Technology*, **45**, 10300-10305. https://doi.org/10.1021/es202401p

[116] Paerl, H.W., Plaas, H.E., Nelson, L.M., Korbobo, A.S., Cheshire, J.H., Yue, L., *et al.* (2024) Dual Nitrogen and Phosphorus Reductions Are Needed for Long-Term Mitigation of Eutrophication and Harmful Cyanobacterial Blooms in the Hydrologically-Variable San Francisco Bay Delta, Ca. *Science of the Total Environment*, **957**, Article ID: 177499. https://doi.org/10.1016/j.scitotenv.2024.177499

[117] Villate, F., Iriarte, A., Uriarte, I., Intxausti, L. and de la Sota, A. (2013) Dissolved Oxygen in the Rehabilitation Phase of an Estuary: Influence of Sewage Pollution Abatement and Hydro-Climatic Factors. *Marine Pollution Bulletin*, **70**, 234-246. https://doi.org/10.1016/j.marpolbul.2013.03.010

[118] Carstensen, J., Andersen, J.H., Gustafsson, B.G. and Conley, D.J. (2014) Deoxygenation of the Baltic Sea during the Last Century. *Proceedings of the National Academy of Sciences of the United States of America*, **111**, 5628-5633. https://doi.org/10.1073/pnas.1323156111

[119] Fennel, K. and Testa, J.M. (2019) Biogeochemical Controls on Coastal Hypoxia. *Annual Review of Marine Science*, **11**, 105-130. https://doi.org/10.1146/annurev-marine-010318-095138

[120] Painting, S., Foden, J., Forster, R., van der Molen, J., Aldridge, J., Best, M., *et al.* (2013) Impacts of Climate Change on Nutrient Enrichment. *MCCIP Science Review*, **2013**, 219-235.

[121] Katsanevakis, S., Stelzenmüller, V., South, A., Sørensen, T.K., Jones, P.J.S., Kerr, S., *et al.* (2011) Ecosystem-based Marine Spatial Management: Review of Concepts, Policies, Tools, and Critical Issues. *Ocean & Coastal Management*, **54**, 807-820. https://doi.org/10.1016/j.ocecoaman.2011.09.002

[122] Kelly, C., Gray, L., Shucksmith, R.J. and Tweddle, J.F. (2014) Investigating Options on How to Address Cumulative Impacts in Marine Spatial Planning. *Ocean & Coastal Management*, **102**, 139-148. https://doi.org/10.1016/j.ocecoaman.2014.09.019

[123] Foley, M.M., Halpern, B.S., Micheli, F., Armsby, M.H., Caldwell, M.R., Crain, C.M., *et al.* (2010) Guiding Ecological Principles for Marine Spatial Planning. *Marine Policy*, **34**, 955-966. https://doi.org/10.1016/j.marpol.2010.02.001

[124] Papadopoulou, N., Smith, C.J., Franco, A., Elliott, M., Borja, A., Andersen, J.H., *et al.* (2025) 'Horses for Courses'—An Interrogation of Tools for Marine Ecosystem-Based Management. *Frontiers in Marine Science*, **12**, Article 1426971. https://doi.org/10.3389/fmars.2025.1426971

[125] Vitousek, P.M., Hättenschwiler, S., Olander, L. and Allison, S. (2002) Nitrogen and Nature. *AMBIO*: *A Journal of the Human Environment*, **31**, 97-101. https://doi.org/10.1579/0044-7447-31.2.97