

Ecological Connectivity in Estuarine and Coastal Marine Environments: Anthropogenic Effects

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Abstract

Ecological connectivity links estuarine and coastal marine habitats across seascapes via the movement of organisms and the action of physicochemical processes that also modulate the structure and function of ecosystems. As such, it plays an important role in the sustainability and resilience of estuarine and coastal marine environments affected by increasing anthropogenic climatic and non-climatic drivers of change. The health and functionality of these environments are coupled to ecological connectivity over variable spatial and temporal scales along the land-ocean continuum. The importance of ecological connectivity is manifested clearly at the land-sea interface in areas of high biotic productivity, biodiversity, and ecosystem services that provide goods and benefits to humankind. Ecological connectivity is a multifaceted process in these coastal ecosystems facilitated by the movement of biota (propagules, individuals, populations), nonliving materials (nutrients, organic matter, sediments), and energy from one location to another mediated by water flow, and it includes structural and functional linkages across seascapes which are vital for development of productive biotic communities and viable ecosystem service provisions. The disruption of estuarine and coastal marine environments by anthropogenic activities and pressures, as well as by extreme natural events such as hurricanes, tornadoes, earthquakes, and tsunamis, can significantly modify and fragment habitats, alter water circulation and biogeochemistry, impede the movement of organisms and nonliving materials, and reduce population abundance, persistence, and biodiversity as well as ecosystem services. In some cases, increasing anthropogenic activities and pressures, including those that escalate climate change effects, have severed ecological connectivity across extensive coastal seascape areas, decreasing trophic interactions and causing acute shifts in ecosystem structure and function. Multiple interactive

anthropogenic and natural stressors cause the degradation and loss of habitats, alteration of ecological processes and biotic communities, and reduction of ecological connectivity and resilience, posing a threat to the sustainability of estuarine and coastal marine ecosystems. Assessing ecological connectivity in estuarine and coastal marine environments enables investigators to formulate frameworks for designing and achieving the conservation, restoration, and management goals necessary to improve ecosystem conditions. Restoring and maintaining ecological connectivity across seascapes impacted by anthropogenic activities and pressures, while challenging, should be a high priority for management programs focused on the protection and sustainability of estuarine and coastal marine ecosystems.

Keywords

Estuarine and Coastal Marine Environments, Ecological Connectivity, Linkages, Land-Ocean Continuum, Seascapes, Habitats, Anthropogenic Impacts, Ecosystems, Restoration, Resilience, Sustainability, Services

1. Introduction

Ecological connectivity of estuarine and coastal marine environments is a multifaceted process that supports the functionality of ecosystems through biological, chemical, and physical linkages across seascapes associated with the movement of biota (propagules, individuals, populations), nonliving materials (nutrients, organic matter, sediments), and energy from one location to another mediated by water flow. Organism migrations (seasonal, foraging, and spawning migrations) and their outcomes as well as shifting organism distributions due to anthropogenic climatic and non-climatic drivers of change are major factors affecting ecological connectivity of these environments. The spatial distribution and structure of habitats are significant factors determining organism abundance and trophic interactions in biotic communities across seascapes. The type of species inhabiting an area influences ecological connectivity because the movement of a species can result in functionally connected habitat patches even though they may be structurally isolated. In contrast, structurally connected habitats may not be functionally connected [1].

Two types of ecological connectivity are recognized in the literature: functional connectivity and structural connectivity. As recounted by Metaxas *et al.* [2], functional connectivity refers to the movement of organisms, nonliving material, and energy across seascapes, and structural connectivity relates to the physical aspects of habitats and their spatial arrangement, habitat patches, or network configurations. Ecological interactions and linkages are important in the process, affecting biotic productivity, biomass, trophic webs, and ecosystem functional sustainability [3]-[8].

Anthropogenic activities and pressures that alter water circulation, biotic com-

munities, and habitats can hinder or arrest ecological connectivity. Climate change is an increasingly significant driver of change interacting with and exacerbating other anthropogenic stressors that impact connectivity; the adverse effects are amplified in coastal watersheds and at the land-sea interface due to disproportionate human population growth, development, and activities [9] [10]. The infrastructure of coastal built communities is particularly susceptible to effects of climatic-driven sea-level rise, as well as tornadoes, earthquakes, tsunamis, and other hazardous natural events, and the adverse effects extend into contiguous estuarine and coastal marine environments [11].

Estuarine and coastal marine ecosystems are not isolated entities but are functionally diverse as interactive components of the land-ocean continuum. Physical, chemical, and biological processes occurring in coastal watersheds influence ecological connectivity of terrestrial habitats and at the land-sea interface [1]. For example, land-derived nitrogen and phosphorus inputs from fertilizer use and other anthropogenic activities have led to serious eutrophication and hypoxia problems in many estuarine and coastal marine environments, altering the functional connectivity along coastal seascapes and causing multiple adverse impacts on biotic communities and habitats that have reduced ecosystem services; climate change has accelerated the impacts [10]-[18]. Paerl *et al.* [15] noted that the effects of interactive physical factors and nutrient dynamics are critical determinants of biotic community production along the freshwater-coastal marine continuum.

Highly variable physical, chemical, and biological processes modulate organism activities and affect ecological conditions across the seascape, a feature defined as a wholly or partially submerged heterogeneous marine landscape comprised of interactive biotic communities, habitats, and ecosystems [19]-[22]. Numerous and intense anthropogenic activities and pressures can disrupt the natural cycles, habitats, and ecosystem conditions across a coastal seascape, making it difficult for investigators to discriminate and assess the interactive factors involved, thereby challenging coastal managers tasked with remediating the impacts [17] [23]. Ecological connectivity along the land-ocean continuum is important for sustainability of ecosystem structure, function, and services, particularly in estuaries where environmental conditions are highly variable and influenced by many anthropogenic activities and pressures [1] [24]. Seascape configurations exhibit complex linkages of habitats and functions in space and time [3] [24]. These linkages are crucial for formulating effective management and conservation plans to protect and maintain ecosystem structure and function, to address impacts of anthropogenic and extreme natural events, and to design marine protected areas and other environmental controls for promoting the resilience and sustainability of populations, biotic communities, and habitats [3] [25]. This review article examines the environmental and biological factors involved in ecological connectivity of estuarine and coastal marine ecosystems, and the anthropogenic activities and pressures that affect them.

2. Ecological Connectivity

Ecological connectivity links estuarine and coastal marine habitats across a seascape system via the movement of organisms and the action of physicochemical processes that also modulate the structure and function of ecosystems. Hence, it plays an important role in ecosystem resilience and sustainability in estuarine and coastal marine environments in the face of increasing anthropogenic climatic and non-climatic drivers of change. Management efforts are needed to restore ecological connectivity of impaired ecosystems and the functionality of impacted biotic communities and habitats.

Estuaries and coastal marine waters are important interfaces between coastal lands and the pelagic waters of the open ocean in which ecological connectivity is vital for maintaining productive biotic communities and trophic webs. Sheaves [3] recounted that these waters are part of the coastal ecosystem mosaic consisting of multifaceted linkages of habitats, biotic communities, and ecosystems at the interface of the land and sea (*i.e.*, freshwater, wetland, estuarine, and coastal ecosystem complexes) and thus serve as a key coupling between terrestrial and off-shore marine ecosystems. Heterogeneous habitats in these coastal ecosystems display multiple scales and configurations, which are important because connectivity of diverse habitats, ecosystems, and resources promotes growth, fitness, survival, and improved functionality of estuarine and marine organisms. Keeley *et al.* [6] conveyed that estuaries exemplify complex, dynamic, and productive cross-scale dependent systems with interconnections that support a diversity of species, habitats, and ecosystem services, including substantial resources of societal value. Measuring and assessing ecological connectivity in these environments is challenging because of highly variable water flow, life-history characteristics, and complex movements of organisms, nutrients, organic matter, and energy across heterogeneous habitat patches and other seascape structural configurations that often lack distinct physical boundaries [26]. Seascape spatial structural features are significant because they can hinder or facilitate the movement of organisms, nonliving material (nutrients, organic matter, sediments), and energy that influence functional connections across seascapes, population persistence, and the dynamic processes of ecological connectivity [6] [27].

Pittman *et al.* [21] defined seascape ecosystems as complex heterogeneous spaces characterized by the translocation of biotic, chemical, energy, and material components critical for trophic connectivity of estuarine and coastal marine populations and biotic communities in habitats across a range of spatial and temporal scales. In regard to the scope of this article, they include fringing wetlands (salt marshes, mangroves, and seagrasses), estuarine waters, and coastal marine ecosystems, such as intertidal and subtidal benthic habitats, oyster and coral reefs, as well as coastal neritic waters. Examples of conspicuous biotic movements linking habitat and ecosystem components across seascapes as part of life-history and ecological connectivity processes are faunal spawning and feeding migrations, refuge migrations, tidal and vertical migrations as well as egg, larval, and plant propagule

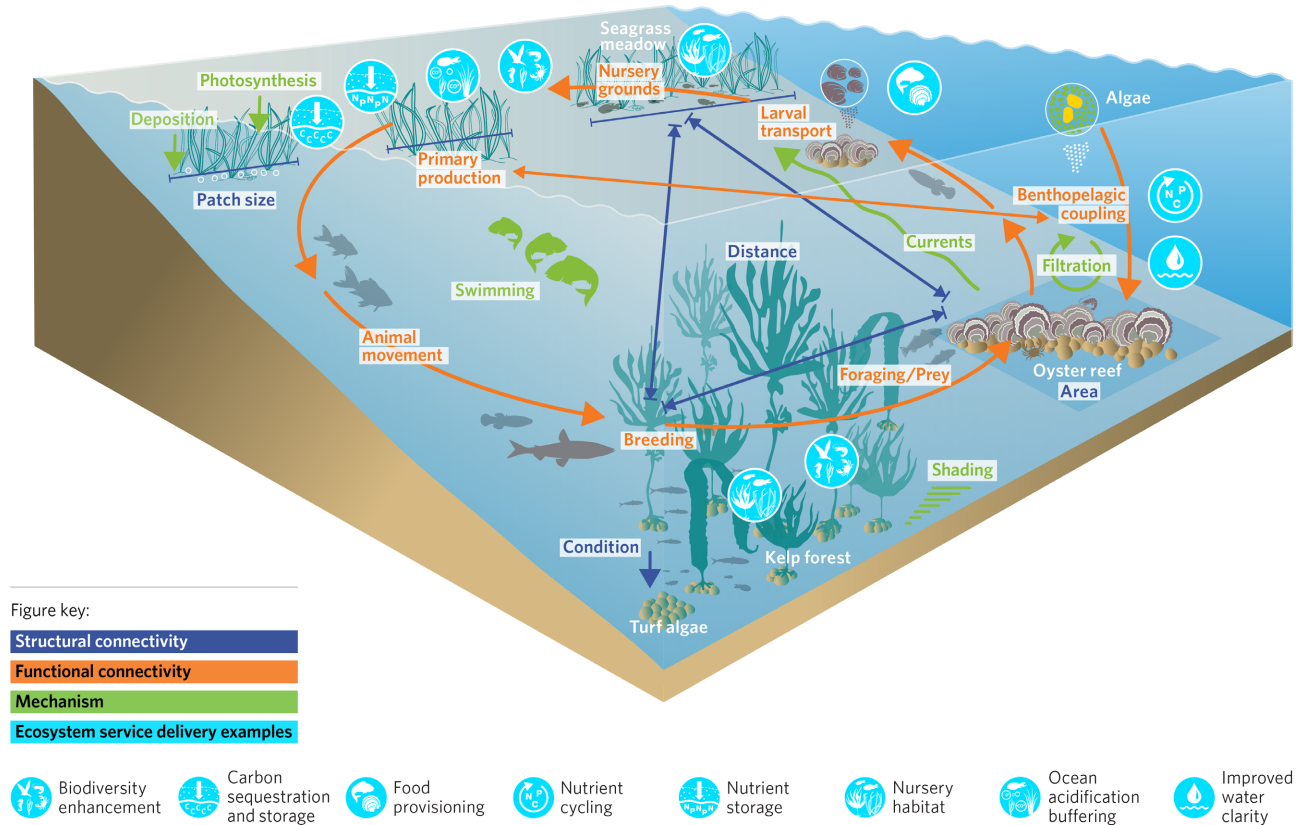
dispersal. Daily movements of organisms connect different habitats within a seascape [28]. Many coastal organisms depend on more than one habitat for success; therefore, organism life histories create complex connections between habitats across seascapes [3]. As such, organism life-history traits, system hydrodynamics, and material inputs and exports in an area can all play significant roles in maintaining ecological connectivity of coastal ecosystems.

Boström *et al.* [19] reviewed faunal responses to habitat patches and seascape configurations, with fragmentation being a dynamic process affecting species composition, spatial ecological patterns, and ecosystem function. Habitat degradation and fragmentation due to anthropogenic activities and pressures result in nonlinear decreases in patch connectivity [29]. Interconnected habitats and seascapes are important for the sustainability of healthy ecosystems and their services which provide important societal goods and benefits, such as recreational and commercial fisheries, mariculture products, pharmaceutical substances, energy generation, pollution mitigation, and carbon sequestration. Nutrient cycling and exchanges, sediment and other material inputs, and organism dispersal and food web interactions also support diverse pathways interlinking ecosystems and functions [3] [6] [8] [29] [30]. However, there is currently incomplete understanding of how estuarine and coastal marine organisms respond to habitat fragmentation and other spatial and temporal drivers of change associated with ecosystem configurations along seascapes [19].

Ecological connectivity has been investigated within the concepts of landscape connectivity, estuarine connectivity, and seascape connectivity by examining biodiversity, habitat (patch) configurations, trophic dynamics, and ecosystem condition. A number of mechanisms modulate connectivity in estuarine and marine environments; **Figure 1** depicts how structural connectivity, functional connectivity, mechanisms, and ecosystem service delivery relate [8]. A major focus is the determination of whether habitats are structurally or functionally connected. Connectivity patterns in habitats across seascapes vary with species, their life stages, and environmental settings, reflecting complex interactions among processes, stressors, habitats, and biotic communities. Connectivity of patches within habitats can increase via multi-directional flow of propagules, nonliving matter, and energy which enhances ecosystem functionality [29]. In highly dynamic estuarine and coastal marine environments, habitat patches and patch mosaics often exhibit considerable spatial and temporal variation and longevity; connectivity or linkages can decrease markedly through time in some of these systems especially due to the impacts of anthropogenic stressors and extreme natural events, leading to greater fragmentation, habitat loss, and declining ecosystem function that degrade biotic communities and diminish ecosystem services [3] [8] [19] [29].

Environmental conditions and biotic factors determine how estuarine and coastal marine habitats are distributed along seascapes (e.g., seagrasses, mangroves, shellfish beds, coral reefs, kelp forests). The spatial configurations and ecological connectivity of these habitats influence their vulnerability and resilience in

SCHEMATIC FIGURE ILLUSTRATING HOW STRUCTURAL CONNECTIVITY, FUNCTIONAL CONNECTIVITY, MECHANISMS AND ECOSYSTEM SERVICE DELIVERY RELATE



Original figure from Preston *et al.* is shown with no changes. Link to the Creative Commons License is <http://creativecommons.org/licenses/by/4.0/>.

Figure 1. Schematic figure illustrating how structural connectivity, functional connectivity, mechanisms, and ecosystem service delivery relate. Examples of structural connectivity are denoted by blue arrows and font, functional connectivity by orange arrows and font, and mechanisms by green arrows and font. The light blue icons provide examples of ecosystem services delivery enhanced by the connectivity across seascape habitats. Credit: Preston, J., Debney, A., Gamble, C., Hardy, M.J., Underwood, G. J. C., Garbutt, A., Harley, J., Baker, R., Dunk, R.M., Grigg, M., Hancock, B.T., Hendy, I.W., La Marca, E.C., Murray, J., Pettorelli, N., Pittman, S.J., Reeves, S.E., Watson, G.J., Watson, S.C.L., Wedding, L.M., Worthington, T.A., Wright, R.A., Yesson, C., and zu Ermgassen, P.S.E. (2025) Seascape Connectivity: Evidence, Knowledge Gaps, and Implications for Temperate Coastal Ecosystem Restoration Practice and Policy. *Npj Ocean Sustainability*, 4, (2025) 33. Doi: 10.1038/s44183-025-00128-3.

the face of environmental stresses and disturbances [31] [32]. The movement and exchanges of materials and energy across landscapes and seascapes are necessary for effective ecosystem functioning [8] [33]. Hillman *et al.* [29] noted that ecosystem functioning is influenced by both ecosystem processes and ecosystem properties, and both components are important to inform understanding of ecosystem process-based connectivity which has focused on material and energy flow through coastal and marine ecosystems. The structure and configuration of patches and patch mosaics, which create heterogeneity in these environments, also affect ecological interactions, ecosystem processes, species distributions, and biotic community productivity. Patch dynamics and population connectivity can vary significantly in different environmental settings due to multiple drivers of change [29].

Preston *et al.* [8] and Tanner *et al.* [25] examined the state of marine functional connectivity and the responses of organisms to seascape structure that supports biodiversity and ecosystem function. They noted that research on marine functional connectivity focuses on spatial transfer of individuals, genes, nutrients, matter, and energy across the seascape. It involves analysis of environmental factors, species biology, ecology, organism behavior, and demography and how they shape connectivity and the development of connectivity metrics useful in marine conservation [25] [34].

Hydrological processes facilitate the movement of biota and materials that sustain functional connections across ecosystems and the viability of biotic communities [6]. Larval dispersal mechanisms in estuarine and coastal marine environments foster greater levels of population connectivity [27] [29]. Dynamic processes, such as multi-directional current flow that vary temporally and spatially, promote biodiverse and productive environments. Many organisms have life-history stages that access different habitats as well, enhancing biodiversity [3] [27]. In estuaries, hydrological processes and their modifications due to anthropogenic activities have a profound effect on longitudinal, lateral, and vertical connectivity which can change rapidly [6] [35]. Water movements (freshwater inflow, estuarine circulation, wave action, tidal currents, tidal mixing, upwelling, etc.) contribute to bi-directional land-ocean connectivity that significantly affects interaction of physical, biogeochemical, and ecological processes. Conversely, fronts and eddy systems, tidal and storm barriers, and some shoreline hardened structures can restrict water circulation and isolate movements of organisms and other components, thereby diminishing ecological connectivity [8]. Estuaries and coastal lagoons exhibit high biotic and habitat heterogeneity; therefore, detailed investigations of multiple habitats are needed to document the hydrodynamic processes governing the transport, transformation, retention, and removal of terrestrial and marine materials that affect connectivity and ecological structure and function in these environments [36].

Ecological connectivity across a mosaic of biogenic faunal and vegetated habitats (e.g., salt marshes, mangroves, and seagrasses, coral and oyster reefs) as well as unvegetated intertidal and subtidal habitats promotes the transfer of nutrients, energy, and biotic components that support trophic webs and dynamics in estuarine and coastal marine environments. Ecosystem engineers (e.g., habitat formers) and key-note species play significant roles in development of robust food webs and enhancement of ecological connectivity. Interconnections of estuarine and coastal marine environments enable the exchange of energy and matter between ecosystems enhancing structure-function relationships, biodiversity, and sustainability of resources (e.g., harvestable fisheries) along the estuarine-marine continuum [3] [8] [37].

Estuaries and coastal marine waters are complex, highly dynamic and interconnected environments with variable ecological processes and biotic communities, spatially heterogeneous habitats, and diverse biotic communities that deliver vital ecosystem services. However, biodiversity in many of these environments is de-

creasing due to climate change, pollution, habitat degradation and loss, as well as other anthropogenic effects [7]. Restoring and maintaining ecological connectivity are pathways for protecting biodiversity and increasing the sustainability and resilience of an impacted estuary or coastal embayment due to anthropogenic disturbances [8] [37] [38]. Thus, restoration of altered and impaired estuarine and coastal marine environments should include actionable goals to improve ecological connectivity such that exchanges of biotic components (larvae, juveniles, and adults) are not impeded so as to promote biodiversity, ecosystem functioning and resilience, and conservation of resources [7].

Seascape ecology is an evolving discipline that examines marine spatial and temporal patterns and their ecological consequences [39]. The application of spatial pattern metrics used to quantify features of terrestrial landscapes has utility in the application of spatial pattern metrics in the marine environment [40]. As noted by Wedding *et al.* [40] in their research focusing on shallow coastal marine applications, quantifying seascape structure using spatial pattern metrics not only has great potential for advancing ecological research but also for the management of marine ecosystems. Wedding *et al.* [39] showed that habitat configuration in these shallow coastal ecosystems is a major factor determining whether ecological connectivity is impeded or facilitated. Advances in marine remote sensing technology have proven valuable in characterizing and quantifying the spatial structure of seascapes (e.g., spatial configuration/orientation of habitat patches, habitat patch size, topographic gradients, etc.) that affect connectivity [8]. An important need is to apply relevant tools to improve understanding of the linkages between the spatial patterns in the sea and ecological processes. Applying the methods of spatial pattern metrics used in terrestrial landscape ecology can yield positive outcomes in seascape ecological research and restoration.

Metaxas *et al.* [2] discussed the approaches for quantifying structural and functional connectivity in coastal and marine ecosystems, that is, the configuration of seascapes and habitats as well as the response of organisms to the seascape configurations. Compiling the information in tabular format (see **Table 1**, page 3 of their perspective paper), the authors showed that the strength and magnitude of connections can be calculated using key metrics (e.g., patch size and fragmentation). There are important physical features targeted in the assessment of structural connectivity, such as coastal frontal zones or adjacent coastal habitats [41]. Networks of habitats, populations, communities, and ecosystems have been used in estimates of functional connectivity [42]. The strength and magnitude of connections across the freshwater-marine continuum can then be calculated to provide measures of connectivity contributions.

Assessing ecological connectivity in estuarine and coastal marine environments, despite its complexities, provides a framework for achieving conservation, restoration (species, biotic communities, and ecosystems), and management goals to improve environmental conditions, ecosystem services, and ecosystem sustainability, such as via the application of marine spatial planning and ecosystem-based

Table 1. Major anthropogenic drivers of change in estuarine and coastal marine environments. Modified from Kennish (2025) [18].

Drivers	
Class 1	(Degrade Water Quality)
	Agricultural, Industrial, and Urban Runoff
	Excessive Sediment/Particulate Inputs
	Nutrient Overenrichment and Organic Carbon Loading
	Harmful Algal Blooms
	Sewage Inputs
	Deoxygenation
	Acidification
	Pathogens
	Chemical Contaminants
	Oil Pollution
	Human Toxicants
	Pharmaceuticals
	Thermal Loading
	Floatables/Plastics/Debris
	(Impact Habitat)
	Population Growth and Coastal Development
Class 2	Land-Use and Land-Cover Changes
	Climate Change
	Freshwater Diversions and Other Hydrological Modifications
	Dams, Dikes, and Other River Structures
	Land Reclamation and Impoundments
	Shoreline Hardening and Ocean Sprawl
	Lagoon Construction
	Marinas and Harbor Facilities
	Dredging and Dredged-Material Disposal
	Mineral Resource Extraction
	Destructive Fishing Practices
	Aquaculture
	Anthropogenic-linked Coastal Subsidence
	(Alter Biotic Communities)
	Eutrophication
	Algal Blooms and Other Light Attenuation Effects
Class 3	Oil Spills and Chemical Toxicants
	Climate Change
	Ocean Warming and Acidification
	Overfishing
	Bottom Trawling
	Intensive Aquaculture
	Seafloor Mining
	Renewable and Nonrenewable Energy Generation
	Transportation and Shipping
	Invasive/Introduced Species
	Noise Pollution
	Floatables/Plastics/Debris

Continued

	(Climate-Linked)
	Climate Change Drivers
	CO ₂ , CH ₄ , NO ₂ , Chlorofluorocarbons, (Greenhouse Gases)
	Warming Temperatures
	Sea-Level Rise
	Seawater Inundation
	Flooding
	Coastal Erosion
Class 4	Precipitation and Land Runoff
	Altered Winds and Water Circulation
	Acidification
	Extreme Events
	Heatwaves
	Tropical Cyclones
	Storm Surges
	Tornadoes
	Droughts

management initiatives [1] [32] [43] [44]. Fang *et al.* [1] and Selkoe *et al.* [45] reported that a wide array of factors affects estuarine and coastal marine ecological connectivity at distinct spatial and temporal scales complicating assessment and remediation programs. This complexity can confound researchers and coastal managers assessing the natural and anthropogenic drivers of change and their effects on ecological connectivity along the land-ocean continuum. Major natural factors affecting ecological connectivity include coastal hydrology (water column stratification, mixing, currents and tidal action), topography, vegetation cover, and sediment flux; principal anthropogenic factors are land-use and land-cover changes, coastal shoreline armoring, land reclamation, river dams, pollution inputs, overfishing, and anthropogenic climate change [1]. Emerging results of seascape genetics and other areas of marine research reflect renewed optimism for greater understanding of these factors and their effects on marine population connectivity and adaptation along seascapes with emphasis on spatial ecological processes.

3. Anthropogenic Effects

Estuarine and coastal marine environments are under increasing pressure from coastal human population growth and development, urbanization, industrialization, and a multitude of regional and global anthropogenic activities that impact coastal ecosystems. Some of the most serious anthropogenic impacts in the world occur in coastal regions where more than 40% of the global population resides within 100 km of the coastline [10] [17]. Projected data collected on coastal cities (2025) by the United Nations show that 271 of the 513 cities in the world with populations greater than 1 million people are located within 100 km of the coastline. These 271 cities collectively represent 52.8% of the largest cities in the world, amounting to 58.5% of the global urban population [46]. Greater numbers of peo-

ple are gravitating to coastal zones because of more favorable economic and social opportunities and conditions [47].

The increased urbanization and industrialization, as well as other anthropogenic activities and pressures associated with greater coastal population growth and development, have caused significant alteration and loss of habitats and decreasing trophic functionality, as well as declining ecological connectivity, ecosystem services, and sustainability of estuarine and coastal marine environments along the land-ocean continuum [1] [3] [17] [48]. Coastal watershed modification is often considerable, with natural land covers converted to residential, commercial, and agricultural development and large areas of constructed impervious surfaces causing significant loss and fragmentation of habitats that facilitate greater runoff of nutrients, sediments, pathogens, toxic chemicals, and other pollutants to rivers, estuaries, and coastal marine waters that reduce ecological connectivity. Upland modifications (e.g., deforestation/silviculture, dams, reservoirs, and channelization of natural waterways) also alter freshwater flow to coastal ecosystems. Land reclamation and hydrological changes (e.g., salt marsh reclamation, freshwater diversions, impoundments, tidal and storm barriers) accentuate impacts, alter ecosystem structure and function, and breach ecological connectivity of habitats.

Anthropogenic activities and pressures have impacted estuarine and coastal marine environments for more than a century [8] [11] [17] [18] [23] [48] [49]. However, increasing population growth and settlement in the coastal zone over the past 50 years have resulted in more significant adverse effects on these environments and their ecosystem service provisions. **Table 1** lists major anthropogenic drivers of change that affect estuarine and coastal marine environments. Halpern *et al.* [50] concluded that anthropogenic activities now threaten 59% of global marine ecosystems. The cumulative impacts can be devastating to ecosystem functionality and sustainability.

Multiple interactive anthropogenic stressors cause the degradation and loss of habitats, alteration of biotic communities, and modification of ecological processes and connectivity that impact sustainability of estuarine and coastal marine ecosystems [8] [23] [29] [51]. Additive, synergistic, and antagonistic interactions of anthropogenic climatic and non-climatic drivers of change and natural stressors result in dramatic adverse conditions leading to detrimental effects on biotic communities, habitats, and ecosystems. The synergistic interaction of multiple drivers of change and the subsequent combined impacts are frequently greater than the sum of the individual impacts [47] [48]. They are manifested fundamentally as nonlinear decreases in connectivity of patches along seascapes and can even lead to collapse of the linkages and failure of ecosystem function [29]. As conditions worsen, trophic interactions severely weaken or collapse as well, shifting ecosystems into a protracted damaged state [8] [27]. Significantly impaired ecosystem processes depress ecosystem service provisions [11].

Estuaries are especially susceptible to climate-change mediated shifts in environmental conditions and anthropogenic non-climatic forcings on biotic commu-

nities that modulate ecological connectivity across seascapes, including rising water temperatures and sea levels, nutrient enrichment and eutrophication, pathogen and chemical contaminant inputs, deoxygenation (hypoxia $< 2.0 \text{ mg O}_2\cdot\text{L}^{-1}$, anoxia $< 0.5 \text{ mg O}_2\cdot\text{L}^{-1}$) and acidification, altered shoreline habitat and water circulation, overfishing and invasive species, and increasing use of resources and space [11] [18] [44] [48]. This is so because estuaries are shallow, partially enclosed bodies of water often bordered by densely populated built communities; thus, they are affected by numerous anthropogenic activities and pressures that more readily impact biotic communities and habitats than in deeper water systems farther removed from developed coastal areas [17] [23] [44] [52]. The combined effects of multi-stressor anthropogenic activities on dynamic and productive estuarine ecosystems can be profound, such as major alterations in the structure and function of biotic communities (e.g., species abundance, distribution, diversity, reproduction, phenology, production, and trophic interactions) and the degradation and loss of biogenic habitats (e.g., salt marshes, mangroves, and seagrasses) important in biogeochemical cycling, transformation of nutrients, filtration of pollutants, trapping of sediments, coastal protection, and ecological connectivity. Anthropogenic impacts are often manifested most acutely in coastal wetlands where the total areal reduction of habitats has been severe, with 50% of the original salt marshes, 35% of the mangroves, and 29% of the seagrasses having been lost or degraded worldwide [53]. In coastal marine waters, kelp forests are declining in all continents, with 40% - 60% of them now degraded [8] [54]. These major habitat impacts have greatly altered the structure, function, and ecological connectivity of coastal ecosystems [17] [48] [51].

Shifts in estuarine conditions are often rapid and substantial as is evident in the case of climate-change driven fluxes [17]. Howarth *et al.* [16] reported that even moderate increases of nutrient delivery and eutrophication in stratified coastal waterbodies can result in the formation of hypoxia and anoxia. Pulses of nutrient inputs result from increasing coastal precipitation and runoff of land-derived nutrients driven by tropical cyclones and other major coastal storms linked to climate change, although some nutrient inputs may derive from offshore ocean waters as well [55]. Eutrophication and hypoxia in many estuarine and coastal marine waters are also attributable to land-use and land-cover changes in coastal watersheds, increasing fertilizer use (10-fold increase since 1950), decreased wetlands habitat area to filter nutrients, and higher water temperatures [17]. Eutrophication and deoxygenation reduce survivorship of estuarine biota, decrease biodiversity and ecosystem productivity, and shift biogeochemical cycling processes, leading to degraded ecosystems [48]. Ecological responses to interactive drivers of change are often nonlinear, with marked structural and functional changes occurring in biotic communities and the loss of ecosystem services [11] [14] [15] [18] [44]. Predicting anthropogenic stressor interactions and ecological outcomes would greatly improve management and conservation plans to effectively address impaired environmental conditions and to promote ecosystem sustainability.

Habitat changes arise from an array of anthropogenic modifications on lower coastal watershed areas, such as the conversion of coastal wetlands to hardened shorelines. Coastal armoring and related structural features along shorelines are especially problematic because they degrade, fragment, or destroy sedimentary habitats while concurrently forming barriers that preclude the movement of organisms, nonliving matter, and energy consequently impacting populations, biotic communities, and habitats over considerable spatial and temporal scales and altering or arresting ecological connectivity across seascapes [30]. Coastal armoring causes a wide range of overt impacts, from marked shifts in hydrodynamics that drive changes in physicochemical conditions and water quality to major modification or loss of habitats and biotic communities [56]. Armored shorelines are mainly constructed to support societal priorities in the coastal zone, including: 1) shoreline and property erosion protection; 2) recreational and commercial activities; 3) marine aquaculture; 4) renewable energy generation, and 5) natural resource extraction [see 30 and the references therein]. Hardened shorelines have replaced more than 50% of the natural coastal shorelines in the United States, accounting for significant loss of habitat and biotic communities and causing ecological impairment [57]. Coastal shoreline modification can greatly disrupt natural processes leading to diminished ecological connectivity and other ecosystem impacts [56]. Ecological effects of hardened shorelines are variable because the armoring structures differ considerably with the type of materials used, their size, areal extent, purpose, and the type of surrounding environment (e.g., salt marshes, mangroves, seagrasses, coral and oyster reefs, sandy beaches, etc.) [56].

Bishop *et al.* [27] and Dugan *et al.* [56] showed that coastal structures used in shoreline hardening (e.g., bulkheads, seawalls, revetments, riprap, retaining walls, etc.) have profound consequences on estuarine and coastal marine ecosystems beyond the sites of their placement, such as changes in the quantity and quality of intertidal and shallow subtidal habitats, populations, biotic communities, food webs, biodiversity, invasive species, ecosystem functioning, and other effects. Particularly noteworthy is that these structures also form stepping stones or corridors for hard-bottom epifaunal and epifloral species which may be non-native to the ecosystem but attracted to the hard substrata [58]. By this process, the artificial structures serve as new habitat enabling an increase in the distribution and range of these non-native hard-bottom species, some of which are dangerous as explosive invasive forms that pose a danger to native species and biotic communities [56]. Furthermore, some shoreline hardening effects are deleterious to benthic habitats on the seaward side of the structures, as demonstrated by reflected waves off of seawalls and bulkheads that steepen the subtidal bathymetric profile because of bottom scour and erosion that removes sediments and benthic organisms near the structures.

Artificial structures can also affect reproduction (birth) and death rates of organisms and their migrations, three factors that strongly influence population sizes [27]. According to Bishop *et al.* [27], changes in migration patterns due to

coastal structures have the added impact of altering the genetic structure of populations, which has far reaching ecological ramifications. Exchanges of materials between coastal lands and aquatic ecosystems can be hindered or precluded by artificial structures that serve as barriers to tidal movements as well as the flow of water from watersheds to discharging waterways. Other anthropogenic structures in the coastal zone affect habitats and biotic communities directly, including human-constructed lagoons, artificial islands and reefs, mariculture and fisheries constructs, shellfish farms, weirs, dikes, docks, piers, sills, boat ramps, wharves, marinas, causeways, tunnels, bridges, jetties and groins, oil and gas platforms, and wind farms. Some structures in coastal and marine environments (e.g., dams, weirs, dikes, and harbor installations) can substantially decrease water movements and organism migrations, directly mitigating ecological connectivity [3]. In addition, artificial marine structures modify dispersal of planktonic and pelagic organisms as well as cause changes in sediment transport and deposition. Shifts in water currents may be significant enough to alter water residence times in estuaries [30].

Construction of hardened shorelines and other marine structures in estuaries eliminates natural habitat resulting in placement loss and severing of ecological connectivity [56]. Dredging operations typically conducted as part of the construction process destroy soft sediment benthic habitat and displace or remove biotic communities inhabiting the benthos. Recovery of the benthic communities and habitat may take several years, with the process involving a succession of organisms that inhabit the impacted sites from opportunistic and pioneering forms to equilibrium assemblages [51] [59]. Similar outcomes are evident from marine mining of mineral aggregates (e.g., sand, gravel, and other resource material) on the seafloor. Besides dredging and mining impacts, shading effects of docks, piers, bridges and other structures in the shallow photic zone of estuaries contribute to the loss of seagrasses and other benthic vegetated habitat, increased benthic community fragmentation, and loss of ecosystem connectivity. The elimination of vegetated coastal ecosystems has additional connotation in that they account for nearly 50% of all carbon burial in marine sediments despite occupying only 2% of the total ocean area, thereby playing a potentially significant role in carbon sequestration and climate change mitigation (Duarte *et al.*) [60] [61]. Farther offshore, the construction of wind farms as well as oil and gas platforms can affect extensive benthic habitat. However, the most significant anthropogenic effects are typically found along shorelines, river mouths, and harbors with heavy armoring most commonly installed as defense structures in waterfront areas to protect people, homes, properties, and infrastructure from rising sea level, storm surges, and flooding associated with hurricanes, nor'easters, tornadoes, earthquakes, tsunamis, and other hazardous events. Shoreline habitats impacted by the siting of artificial structures can be restored with the removal of the structures or shifting them landward to reduce interactions with tides and waves and thus expand habitat space [56].

The desire by many coastal inhabitants to access waterfront properties is

fraught with greater risks and hazards associated with natural environmental disasters and insufficient planning and protection [11]. Coastal development and urbanization are largely responsible for the siting of structures at waterfronts, which remains the main approach by homeowners in lower coastal watersheds to protect their houses and properties from the effects of rising sea level, flooding, and sea-water inundation, despite the recommendations of many coastal experts to use nature-based solutions such as living shorelines, marsh and dune restoration, and wetlands protection to mitigate risk. Escalating coastal development and rising sea level due to climate change contribute to coastal squeeze that is detrimental to shore community resilience and sustainability of ecosystems and resources. These changes are exacerbated by the continued alteration and loss of coastal wetlands and their buffering capacity to protect upland habitats and communities from rising sea level, storm surge, shoreline erosion, inundation, and flooding [62]. The effects of rising sea level, erosion, and construction of artificial structures in the coastal zone have been detrimental to beaches as well, with more than 50% of them retreating landward around the world [1].

Urbanization of coastal watersheds with intensifying development affecting coastlines, foreshore and nearshore areas is the cause of escalating anthropogenic stressors, the transformation of habitats, and modification of biotic communities, ecosystems, and seascapes [11] [30] [51]. Duarte *et al.* [63] termed the increasing anthropogenic development and use of artificial structures and other constructs in coastal and marine environments as “ocean sprawl,” which can substantially alter ecological connectivity in several ways. As noted by Bishop *et al.* [27], hardened shorelines often create barriers that impede organism and nonliving material movement and cause the loss of habitat, which diminishes ecological connectivity and degrades ecosystems. They also form artificial substrates for settlement and growth of epifaunal and epifloral organisms, including opportunistic non-native invasive species, that can proliferate as nuisance biofouling communities detrimental to waterfront properties.

Some engineered structures, however, serve as conduits that facilitate organism and sediment movements and increase natural ecological connectivity. For example, the 4800-km Atlantic Intracoastal Waterway, consisting of extensive areas of dredged channels along the Atlantic and Gulf coasts in the USA, forms a major pathway for organism and sediment movement in lagoonal back-bays and estuaries. In their review of ocean sprawl effects on sedimentary environments, Heery *et al.* [30] documented several major biotic, chemical, and physical outcomes including placement loss, changes in species interactions and biotic community dynamics, nutrient and organic carbon enrichment, material fluxes, contaminant inputs, and altered hydrodynamics, all of which can affect ecological connectivity and ecosystem state. They reported that ocean sprawl is particularly detrimental in sedimentary environments because it removes or transforms marine habitats via the placement of artificial structures which affect sediment-dependent taxa from microbes to demersal fish, with the level of impacts contingent on the size

of the structure and its design as well as the physical, chemical, and biological characteristics of the environment. They concluded that artificial structures may structurally and functionally alter ecological connectivity in coastal and marine environments, but in some cases (*i.e.*, removal or weakening of existing structural barriers), timely responsive actions can promote ecological connectivity. It is also unclear how the changes in connectivity interact with other anthropogenic stressors in these environments, such as nutrient enrichment, contaminant inputs, and land-derived sediment fluxes which can amplify impacts.

Bugnot *et al.* [57] indicated that marine construction contributes greatly to ocean sprawl worldwide. Their study estimated that in 2018 the footprint of marine-built structures amounted to 32,000 km² and altered 1.0 - 3.4 × 10⁶ km² of seascape area around the structures. By 2028, the physical footprint of marine-built structures is projected to increase to 39,400 km². The magnitude of altered natural seascape due to marine construction is significant, and it impacts the structure and function of ecosystems and endangers ecological connectivity extensively across the land-ocean continuum.

Altered dispersal and distribution of organisms and resources due to ocean sprawl can significantly change biotic community structure and function as well as the complexity of trophic webs underpinning biodiversity, as is evident in the weakening of trophic interactions with restricted movements of predators and prey. Barrages and flood gates, for example, block movements of fish and other organisms when closed, which directly threatens ecological connectivity. While biotic community and local habitat modification (*i.e.*, fragmentation and destruction) can also be acute in such settings, they frequently are inadequately assessed in regard to impacts on ecological connectivity due to insufficient funding, technical expertise, or manpower. Therefore, this is an area of coastal research that must be investigated more thoroughly in multiple environmental settings in the coastal zone, particularly in urbanized estuaries and coastal marine environments that are impacted by the interaction of multiple anthropogenic stressors. In addition, there needs to be greater focus on integrating nature-based solutions in environmental remediation programs, including ecological engineering, rather than installing protective hardened structures along waterfront properties to buffer against climate change effects (e.g., rising sea level, storm surges, inundation, and erosion) and non-climatic drivers of change [17]. These natural approaches could significantly improve ecological connectivity in many coastal regions.

A research area of great interest in recent years is the study of the combined effects of anthropogenic climatic and non-climatic stressors on aquatic environmental conditions, which is particularly problematic in estuarine and coastal marine environments where anthropogenic activities and pressures are historically most severe, often leading to pernicious impacts on biotic communities and habitats [17] [48]. The challenges are significant for scientists and coastal managers assessing the array of impacts in these environments attributable to complex interactive anthropogenic climatic and non-climatic drivers of change, the limited

databases collected on them, and the insufficient use of predictive models [18] [64]. The interaction of multiple anthropogenic climatic and non-climatic stressors presents more complex challenges in the study of estuarine and coastal marine environmental impacts than the focus on a single driver of change, such as eutrophication development [18] (Table 2). For example, greater storm activity and elevated precipitation in some regions facilitate runoff from coastal watersheds and the loading of nutrients and organic matter into estuarine and coastal marine waters contributing to eutrophication problems, as is evident in coastal North Carolina waters (USA), such as the Neuse River-Pamlico Sound system [13]-[15] [65]. Over the past 30 years, North Carolina and some other coastal states in the USA have been the sites of more frequent extreme rainfall events caused by high-intensity tropical cyclones linked to climate change that have escalated nutrient inputs to estuaries and coastal marine waters contributing to eutrophication and deoxygenation problems [62].

Table 2. Major interactive factors of climate change, altered land and hydrologic systems, and pollution inputs that exacerbate impacts and affect ecological connectivity in estuarine and coastal marine environments Modified from Kennish (2025) [18].

Factor	Impact
Warming Temperatures	Strengthen Pycnoclines Reduce Oxygen Transmission to Deeper Waters; Decrease Nutrient Recycling to Surface Waters; Alter Phytoplankton and Vascular Plant Growth and Biomass
Heatwaves and Droughts	Decrease Oxygen Solubility
Coastal Fires	Increase Runoff of Nutrients and Organic Matter to Estuaries and Coastal Marine Waters from Altered Land Surfaces
Sea-Level Rise	Cause Coastal Land Inundation and Erosion; Increase Nutrient and Organic Matter Delivery to Estuarine and Coastal Marine Waters
Storm Surges and Tidal Flooding	Greater Coastal Erosion and More Runoff of Nutrients, Organic Matter, Pathogens, and Chemical Contaminants to Streams and Rivers
Higher Intensity Storms	Freshwater Runoff Pulses; Higher Inputs of Nutrients, Organic Matter, Pathogens, and Chemical Contaminants to Rivers, Estuaries, and Coastal Marine Waters
Greater Precipitation (10% - 20%)	Higher Inputs of Nutrients, Organic Matter, Pathogens, and Chemical Contaminants to Rivers, Estuaries, and Coastal Marine Waters
Land-Use and Land-Cover Changes (More Impervious Surfaces)	More Rapid and Greater Volume of Runoff to Rivers, Estuaries, and Coastal Marine Waters
Increased Land Runoff	Greater Inputs of Nutrients, Organic Matter, Pathogens, and Chemical Contaminants to Rivers, Estuaries, and Coastal Marine Waters

Continued

Modified Hydrologic Regimes	Variable Delivery of Nutrients, Organic Matter, Pathogens, and Chemical Contaminants to Estuaries and Coastal Marine Waters
Higher River Discharges	Facilitate Delivery of Nutrients, Organic Matter, Pathogens, and Chemical Contaminants to Estuaries and Coastal Marine Waters
Altered Flushing and Water Residence Time	Lead to Variable Concentrations of Nutrients, Organic Matter, Pathogens, and Chemical Contaminants in Estuaries
Increased Water Column Stratification	Reduce Vertical Mixing and Oxygen Delivery to Bottom Waters; Decrease Water Column Distribution of Nutrients, Organic Matter, Pathogens, and Chemical Contaminants
Water Circulation Changes	Shift Distribution of Nutrients, Organic Matter, Pathogens, and Chemical Contaminants in Estuaries and Coastal Marine Waters
Increased Wind Velocity	Increase Water Column Mixing and Distribution of Nutrients, Organic Matter, Pathogens, and Chemical Contaminants in Estuaries and Coastal Marine Waters
Hardened Shoreline Structures	Alter or Destroy Natural Habitats; Modify Water Circulation; Reduce Ecological Connectivity

Altered patterns of precipitation leading to variable freshwater discharges to coastal waters result in additional impacts such as harmful algal blooms and changes in water quality, modified biogeochemical cycling, shifting flushing rates, and cascading effects on food webs that can reduce fisheries production and other resources [15]. Sinha *et al.* [66] determined that increases in climate-change induced precipitation during the 21st century will substantially increase total riverine nitrogen loading by $19\% \pm 14\%$ within the continental United States for the “business-as-usual” climate model scenario (RCP8.5), which will pose additional threats to water quality in many coastal aquatic ecosystems already impacted by eutrophication. Projections also indicate heavier regional precipitation intensity (*i.e.*, ~15% - 20% greater), although the regions experiencing heavier precipitation will vary [18].

Gissi *et al.* [67] conducted a cumulative effects study of the combined impact of climate change and local anthropogenic stressors on ecological responses and functional aspects of marine environments. This holistic approach enabled the acquisition of data to estimate the cumulative impacts upon different levels of biological organization and selected biotic components to determine effects on marine biodiversity and other critical metrics at multiple temporal and spatial scales. Their work analyzed 107 studies selected through a systematic literature review. The results of this work, that the combined effects of climate change and local anthropogenic stressors vary between and within ecosystems, is not unexpected considering the significant spatial fluxes of these drivers of change in highly variable estuarine and coastal marine environments. These results indicate that the

combined effects of climate change and local anthropogenic stressors are context-dependent [6]. Thus, it is imperative to conduct detailed studies of the effects of these stressors in multiple environmental settings that can be utilized in management programs to remediate local-scale impacts.

4. Management Programs

Ecosystem-based management is a highly collaborative approach focused on supporting the functionality of ecosystems and the sustainability of ecological connectivity in estuarine and coastal marine environments [44]. As stated by Kennish ([18], p. 289), “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.” These programs recognize the importance of achieving a balance in the intensity of human activities and the ability of estuarine and coastal marine environments to retain viable and sustainable resources as well as ecosystem service provisions [44] [68]–[70]. By instituting a holistic approach to assess and manage ecosystems, these efforts promote ecological connectivity across seascapes.

Ecosystem-based management is a science-based and data-driven framework that integrates ecological, economic, and societal domains and examines the interconnectedness and condition of ecosystems along the freshwater-marine continuum to determine the measures needed to improve the health of the ecosystems, promote conservation of resources, and enhance ecosystem services [11] [71]. An important part of this work is to protect species populations and biotic communities, rehabilitate ecosystem structure and function, and restore damaged habitats to support ecological connectivity and ecosystem services [17]. Multiple stressors are on the rise in coastal ecosystems linked to escalating human population growth and coastal watershed development coupled to greater anthropogenic activities and pressures that impact ecosystems and hinder ecological connectivity [1] [8] [27]. Reducing the interactive effects of anthropogenic climatic and non-climatic drivers of change through comprehensive mitigation programs, improved land-use policies, innovative development and water management plans, and habitat restoration is an effective approach to address these impacts. Mitigation and adaptation programs support efforts to make these ecosystems more resilient to anthropogenic and natural drivers of change [17]. Ecosystem-based management considers the entire ecosystem and its interactive components (*i.e.*, environmental conditions, anthropogenic activities and pressures, and socio-economic factors); therefore, it is an effective pathway for managing land-sea interactions [1] [72] [73].

Ecosystem-based marine spatial planning is a framework based on the principles of ecosystem-based approach and ecosystem-based management of maritime activities and includes a coordinated governance structure that represents a viable

strategy for managing human uses of maritime space with a goal of maintaining ecosystems in a healthy, productive, and resilient condition, while promoting biodiversity, ecosystem services, and reducing or defusing user conflicts [71] [74] [75]. Ecosystem-based marine spatial planning informs coastal managers and policymakers about the spatial distribution of human activities in estuarine and coastal marine waters and concurrently the uses of ecosystems that affect their sustainability, thereby supporting ecological connectivity along seascapes. It utilizes a multidisciplinary approach that encompasses the full array of interactions in an ecosystem including human uses and consideration of socio-ecological processes, while enabling the ordering and accurate assessment of the spatial and temporal distribution of human activities in estuarine and marine environments to achieve ecological, economic, and social objectives, notably resource protection and sustainability, as well as conflict resolution of user groups. Ecosystem-based management and ecosystem-based marine spatial planning have been widely applied globally because of declining conditions of estuarine and coastal marine environments and resources in many regions of the world, together with their diminishing ecosystem services, necessitating more efficient management approaches than employed previously that will yield achievable solutions to advance ecosystem sustainability [44].

Restoration programs across coastal seascapes mitigate anthropogenic impacts on estuarine and coastal marine environments, improve structure-function relationships in damaged ecosystems, and revitalize ecological connectivity by enhancing the movement of organisms, nonliving material, and flow of energy between habitats. Implementing a multi-habitat and multi-trophic restoration plan incorporating seascape ecological connectivity applicable to habitat patches and across habitat mosaics can yield significant positive outcomes over wider spatial scales that improve broader functioning and resiliency of estuarine and coastal marine ecosystems [8]. This is a key pathway to support ecosystem-based management and marine spatial planning initiatives for protecting and promoting viable biotic communities, biodiversity, structurally and functionally sound habitats, and valuable ecosystem service provisions. The use of nature-based solutions (e.g., living shorelines, oyster reefs, and restored wetlands) and bioremediation is rapidly gaining favor as additional applications for protecting and maintaining estuarine and coastal marine habitats impacted by anthropogenic activities and extreme natural events. These measures are also useful for policy development to improve coastal environmental conditions over the long term.

5. Conclusions

Ecological connectivity of estuarine and coastal marine environments is a multifaceted process involving biological, chemical, and physical linkages between habitats and ecosystems associated with the movement of biota (propagules, individuals, populations), nonliving materials (nutrients, organic matter, sediments), and energy from one location to another mediated by water flow. It is critical for ef-

fective functioning of seascapes across space and time via the interaction of terrestrial, atmospheric, aquatic, and socioecological processes that also affect the structure and function of ecosystems. Ecological connectivity plays an important role in sustainability and resilience of estuarine and coastal marine ecosystems in the face of increasing anthropogenic climatic and non-climatic drivers of change.

Estuaries and coastal marine waters are important interfaces between coastal lands and the pelagic waters of the open ocean in which ecological connectivity plays an important role in maintaining productive biotic communities and functioning trophic webs. The disruption of physical, chemical, and biotic processes and habitats across seascapes by anthropogenic activities and pressures, as well as by extreme natural events (e.g., hurricanes, tornadoes, earthquakes, and tsunamis), can significantly modify and fragment habitats, alter hydrodynamics and biogeochemistry, impede the movement of organisms and nonliving materials, arrest ecological connectivity, and reduce population abundance, persistence, and biodiversity as well as ecosystem services that provide goods and benefits to humankind. Because there are multiple interactive ecosystem processes and anthropogenic stressors that occur over an array of spatial and temporal scales and habitat types, it is often difficult to characterize ecosystem functioning and the interactions of factors and processes that influence biotic communities and delivery of ecosystem services in estuarine and coastal marine environments. For example, coastal watershed modification in many regions due to human activities is acute with natural land covers often converted to residential, commercial, and agricultural development. In addition, large areas of constructed impervious surfaces cause significant habitat fragmentation and loss as well as accelerated runoff that facilitates inputs of nutrients, sediments, pathogens, toxic chemicals, and other pollutants to rivers, estuaries, and coastal marine waters that can significantly reduce ecological connectivity, impacting biotic communities and trophic webs.

Ecological connectivity is a critically important process supporting healthy functionality of estuarine and coastal marine environments and the ecosystem services they provide. While there is general consensus regarding the significance of ecological connectivity in these environments, the process consists of multiple components that are complex and often challenging for researchers and coastal managers to evaluate because of substantive fluxes in physical, chemical, and biotic factors. A major focus is the determination of patch configurations in seascapes and whether habitats are structurally or functionally connected. Connectivity patterns in habitats across seascapes vary with species, their life stages, and environmental settings, reflecting complex interactions among processes, stressors, habitats, and biotic communities. Assessing ecological connectivity in estuarine and marine environments provides a working framework for achieving conservation, restoration, and management goals to improve environmental conditions, ecosystem services, and ecosystem sustainability.

Connectivity among a mosaic of biogenic faunal and vegetated habitats (e.g.,

salt marshes, mangroves, seagrasses, coral and oyster reefs) as well as unvegetated intertidal and subtidal habitats promotes the transfer of nutrients, energy, and biotic components that support trophic webs and dynamics in estuarine and coastal marine ecosystems. However, increasing anthropogenic activities and pressures, including those that have escalated climate change impacts over the past several decades, disrupt or sever ecological connectivity across extensive seascape areas, degrading trophic interactions and reducing biodiversity, causing significant shifts in ecosystem structure and function, decreasing resilience, and reducing ecosystem services. Coastal armoring and related structural features along shorelines are particularly problematic because they degrade, fragment, or destroy sedimentary habitats while often forming barriers that preclude the movement of organisms, nonliving matter, and energy, thereby altering or arresting ecological connectivity.

Multiple stressors are on the rise in coastal ecosystems linked to escalating human population growth and coastal watershed development driving anthropogenic activities and pressures that impact ecosystems. Mitigating the impacts of anthropogenic climatic and non-climatic drivers of change through improved land-use policies, innovative development frameworks, water management plans, and habitat restoration is an effective approach to enhance ecological connectivity and to improve ecosystem sustainability and resilience. As such, ecosystem-based management and ecosystem-based marine spatial planning are particularly useful management initiatives for achieving these positive outcomes. Restoration of damaged habitats across coastal seascapes also improves the structure-function relationships in ecosystems and revitalizes ecological connectivity by promoting the movement of organisms and flow of matter and energy between habitats. An important positive outcome is the greater sustainability of ecosystem services for human use.

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Conflicts of Interest

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

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