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SPECIAL FEATURE: CURRENT TOPICS IN ECOLOGY

**Biodiversity and Its Ecological Functions in East-Asia and Pacific Region: Status and Challenges**

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# Ecological connectivity between land and sea: a review

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**Abstract** Land–sea ecological connectivity refers to the interaction (convenience or hindrance) of certain physical, chemical and biological processes between terrestrial and marine ecosystems. Research on land–sea ecological connectivity can provide important scientific bases for the conservation and restoration of biodiversity and ecosystems in terrestrial and coastal areas. On the basis of a literature summary of ecological connectivity, this paper focuses on the following: (1) summarizing basic concepts, representative phenomena on multiple spatiotemporal scales, and analysis methods of land–sea ecological connectivity; (2) discussion of the applications of land–sea ecological connectivity; (3) discussion of the relationship between human activities and land–sea ecological connectivity; (4) presentation of perspectives and recommendations on ecological restoration, protection, and biodiversity research, with emphasis on the principle of land–sea ecological connectivity. On the whole, we believe such connectivity in a region varies with changes in multiple physical and artificial factors, such as climate, land cover, biotic community and human activities. Human activities such as land use, engineering construction, urbanization and industrialization have continuously increased and cause irreversible disturbance and destruction of land–sea ecological connectivity, thereby threatening biodiversity and ecosystem services at various spatiotemporal scales. Hence, achievements of theoretical research and practical experience in ecological connectivity should be fully applied in coastal areas to maintain and restore land–sea ecological connectivity and remedy various problems that arise from the blockage and damage of ecosystem services.

**Keywords** Ecological connectivity · Land and sea · Coastal zone · Biodiversity · Ecosystem services

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## Introduction

Connectivity has become one of the most widely used terminologies in the biological sciences, and the concept of ecological connectivity has been developed and widely accepted (Sheaves 2009). This concept has been the subject of several studies worldwide. Research focusing on ecological connectivity in offshore and inshore areas emerged in the mid-1990s but lagged behind research focusing on terrestrial areas. Moreover, research into offshore and inshore areas is more complex and difficult than that into terrestrial areas, mainly because of data deficiencies (Du et al. 2015).

With the acceleration of urbanization in coastal zones worldwide, economic centers in coastal countries have transferred toward coastal areas. As a result, more than half the global population lives within 100 km of the coast (Primavera 2006). Coastal zones have become the most active and vibrant for social and economic activities (Halpern et al. 2015). However, under global warming, sea-level rise, intensified storms, and increas-

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**Table 1** Basic concepts of ecological connectivity

| Concepts | Definitions | References |
|---|---|---|
| Landscape connectivity | The ability of landscape to facilitate or impede movement among habitat patches, support fluxes of energy, organisms and materials (e.g. seeds, biomass, pollen, nutrients, sediments), and long-term persistence of biodiversity | Pelorosso et al. (2016) |
| Estuarine connectivity | The dependence of fish production and population dynamics on dispersal and migration among multiple habitats | Sheaves (2009) |
| Hydrologic connectivity | Water-mediated transport of matter, energy and organisms within or between elements of hydrologic cycle | Freeman et al. (2007) |
| Patch connectivity | More applied to metapopulation ecology, connectivity represents characteristics of each patch; however, this definition does not consider ecological connectivity between patches | Tischendorf and Fahrig (2000) |
| Structural connectivity | Configuration of landscape and habitat patches that is typically quantified using landscape metrics such as patch size, isolation, and fragmentation that are believed to act as conduits or barriers to movement | Bishop et al. (2017) |
| Functional connectivity or behavioral connectivity | The degree to which landscape facilitates or obstructs the movement of organisms between landscape patches | Niculae et al. (2016) |

ing human demand for natural resources, more than half of world's beaches have retreated because of erosion and artificial destruction. Fragmentation and isolation of terrestrial and marine ecosystems have been exacerbated, leading to severe problems such as habitat degradation, biodiversity loss and ecosystem service reduction. Consequently, to protect coastal habitat, preserve biodiversity and improve the adaptive capacity of coastal communities against climate change, scientists in developed countries have realized that studies of connectivity of ecosystems between land and sea may provide essential knowledge and a scientific basis for not only ecosystem conservation and restoration but also for freshwater and marine resource exploitation. However, in most developing countries, this has not been established as a goal of conservation of coastal ecosystems and biodiversity because of lagging academic research and lack of public awareness of related issues (Ministry of Environmental Protection of the People's Republic of China 2008; LaPoint et al. 2015).

This paper focuses on the following: (1) summarizing basic concepts, representative phenomena on multiple spatiotemporal scales, and analysis methods of land–sea ecological connectivity; (2) discussion of the applications of land–sea ecological connectivity; (3) discussion of the relationship between human activities and land–sea ecological connectivity; (4) presentation of perspectives and recommendations for ecological restoration, protection and biodiversity research, with emphasis on the principle of land–sea ecological connectivity.

## Land–sea ecological connectivity

### Definition of ecological connectivity

Connectivity is one of the fundamental concepts in topology. Generalized connectivity in ecology is defined as physical, chemical, biological processes and their interactions between ecosystems in various layers of the earth. This concept also includes energy flow and biological migration caused by external environment change. After being introduced in landscape ecology, it was defined as follows: "from the surface structure, describe the objective degree of interrelationship among different units in the landscape" (Sheaves 2009; Du et al. 2015; LaPoint et al. 2015). With the development of spatial ecology and conservation biology, ecological connectivity has gradually evolved into an important concept in natural sciences. Ecological connectivity has been widely used in restoration of species, communities and ecosystems of land– and sea–sensitive areas, and landscape design. However, because of its complexity, a uniform definition of ecological connectivity has not been established among researchers (Kool et al. 2013; Du et al. 2015). By inspecting and comparing journal articles on ecological connectivity and ecology (Tischendorf and Fahrig 2000; Sheaves 2009; Niculae et al. 2016; Pelorosso et al. 2016; Bishop et al. 2017), we summarized synonyms for the terminology of connectivity (Table 1).

Landscape connectivity has been the most frequently investigated issue in the published literature. Table 1 shows the definition of landscape connectivity. Although definitions vary by scholar, the following similarities are observed: (1) studies emphasize the dynamics of landscape structure and state that connectivity is the connection or interaction between species and specific landscapes/habitats. In other words, landscape structure is influenced by species and connectivity is based on habitat (Tischendorf and Fahrig 2000). (2) The degree of species perception of habitats is determined by their lateral, vertical, large-scale or small-scale daily activities, or seasonal migration. (3) All reactions caused by various environmental changes in a habitat promote or impede the flow of ecological resources among various

**Table 2** Classification of various aspects of land–sea ecological connectivity

| Category | Terminology |
|---|---|
| Behavioral connectivity or functional connectivity (1–6) | 1. Tidal migration of neritic animals (or fish) |
| | 2. Foraging migration of neritic animals (or fish) |
| | 3. Breeding migration of neritic animals (or fish) |
| | 4. Stranded dead marine products on the shore |
| | 5. Bird moving foraging |
| | 6. Bird seasonal migration |
| Bio-geochemical connectivity or process connectivity (7–9) | 7. River nutrient transport |
| | 8. Saltwater intrusion |
| | 9. Delta development |

patches. Even in the same landscape, connectivity varies with species and community. Although some habitat patches are structurally connected, they may not be connected in terms of functionality. Likewise, although some habitat patches are structurally isolated, they can be functionally connected with the movement of species (Tischendorf and Fahrig 2000). That is, connectivity depends on species. This paper focuses on an analysis and summary of bidirectional ecological connectivity between land and sea.

## Representative phenomena and multiscale characteristics of land–sea ecological connectivity

We picked the top nine representative phenomena from the literature to substantiate the existence of land–sea connectivity from different perspectives (Table 2).

These nine phenomena cover multiple disciplines and exhibit significant cross-scale characteristics (Fig. 1).

Phenomena 1–3 describe the functional connectivity reposed on the migration of a neritic organism between different habitat patches during its life development. For example, in tropical and subtropical coastal areas, its migratory range roughly encloses a system consisting of coral reef, mangrove, estuarine and lower fluvial ecosystems. Regarding the spatial scale of migration, breeding migration is usually over a notably longer distance than tidal migration and foraging migration.

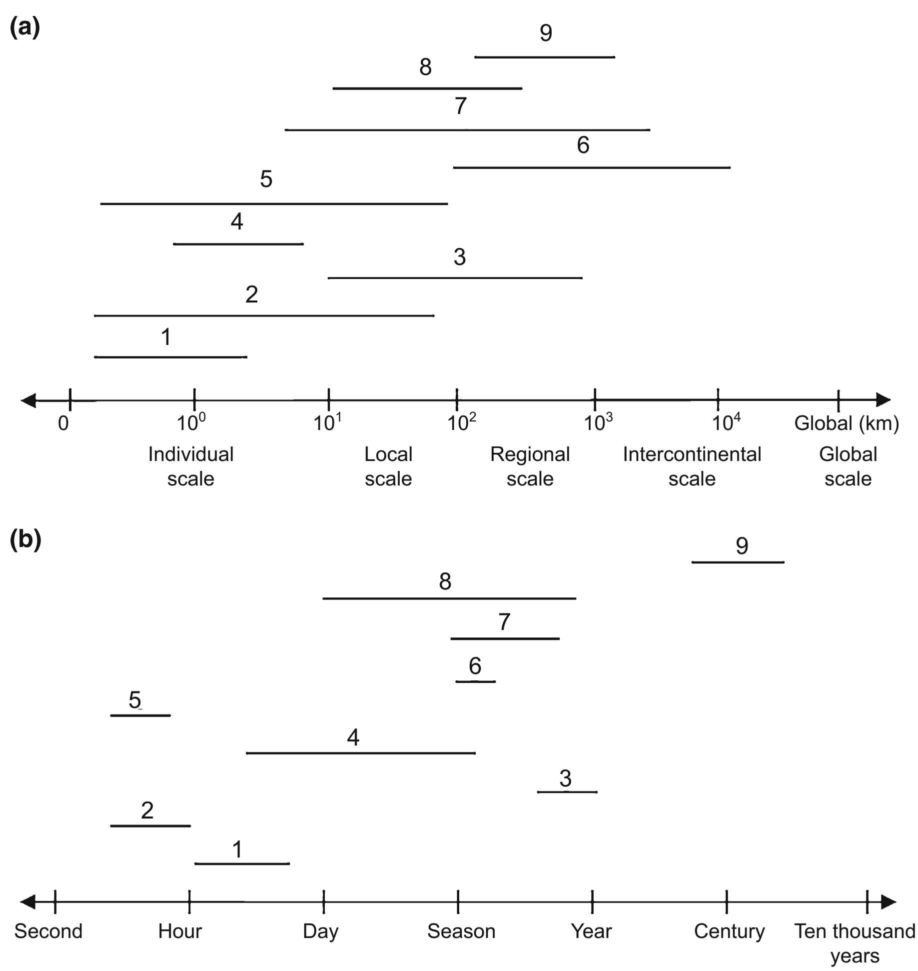


**Fig. 1** Conceptual perspective of cross-scale characteristics of various types of land–sea connectivity (**a** spatial scale; **b** temporal scale. Numbers correspond to Table 2)

For example, historically, the breeding migration distance of salmon in the Thames River exceeds 100 km (Polis et al. 1997; Griffiths et al. 2011; Mei 2013). By contrast, the tidal migration distance of the common Japanese conger is only a few kilometers, and the foraging migration distance of the Japanese Spanish mackerel is only a few tens of kilometers. Regarding the temporal scale of migration, breeding migration should be categorized as seasonal, annual, or perennial, whereas tidal and foraging migration should be categorized as conventional migration within a day.

Phenomenon 4 explains the flow of biomass and energy from the marine system to the terrestrial system, among which the shore drift of algal and stranded marine mammals are the two most representative events (Polis and Hurd 1996; Polis et al. 1997; Lyons et al. 2009; Bogomolni et al. 2010; Truchon et al. 2013). Drift algal blooms are mainly subject to light, water temperature, nutrients and other seasonal factors, and typically peak in late summer or early autumn. Stranding of marine mammals is attributed to harmful algal blooms, disorientation, and climatic factors. Marine mammal stranding may be a small-scale event of a single animal or a large-scale event of animal groups. Such stranding and drift algal blooms are key indicators of ocean health.

Phenomena 5 and 6 describe the daily (short-distance) and seasonal (long-distance) migration of birds, respectively. They strictly pertain to intermittent and functional connectivity, and both represent cross-scale connectivity stepping from patch to global scales (Polis et al. 1997; Buelow and Sheaves 2015). In fact, although structural connections do not necessarily exist among the flyways of migratory birds, there is some functional connectivity with certain intermittence because of the movement foraging and refueling of the birds during seasonal migration. Furthermore, the spatial range of bird movement foraging and distance of bird seasonal migration are usually larger than the foraging migration of neritic organisms (Polis and Hurd 1996; Polis et al. 1997; Nagelkerken et al. 2015).

Phenomena 7 and 8 are the most widely known cross-scale connectivity in the land–river–sea system. In this system, nutrients discharged by industrial and agricultural production are transported to estuaries and coastal waters because of water flow. These nutrients can nourish the organisms in offshore ecosystems. However, excessive nutrients result in serious land-based pollution, such as coastal zone eutrophication, marine hypoxia and ocean acidification (Zhang 2011), and can significantly disturb the balance of the offshore ecosystem (Velez et al. 2016). Moreover, owing to unreasonable use of water resources, sea-level rise, coastal storm surge increase and coastal ground water-level change, offshore seawater flows into inland areas along river channels or through underground permeable strata. This causes soil salinization, which is a widespread and serious environmental issue in coastal areas (Colombani et al. 2016). The spatial scale of river nutrient transport depends on watershed basins and river systems, as for the temporal variations, for example, the seasonal variations of estuary nutrient flux are subject to river runoff (Heyman and Kjerfve 2001). Saltwater intrusion usually occurs on local and regional scales in estuary and coastal areas, and lacks substantial seasonal variation.

**Table 3** Species recommended for research on land–sea ecological connectivity

| Class | Species |
|---|---|
| Fish | *Acipenser sinensis* |
| | *Coris dorsomacula* |
| | *Hucho taimen* |
| | *Japanese eel* |
| | *Lutjanus argentimaculatus* |
| | *Lutjanus fulvus* |
| | *Lutjanus gibbus* |
| | *Naso brevirostris* |
| | *Psephurus gladius* |
| | *Salmon* |
| Birds | *Limosa limosa* (Black-tailed Godwit) |
| | *Gavia arctica* (Black-throated loon) |
| | *Himantopus himantopus* (Black-winged Stilts) |
| | *Ciconia* |
| | *Ciconia nigra* |
| | *Pelecanus crispus* (Dalmatian pelican) |
| | *Relict gull or Central Asian gull* |
| | *Larus saundersi* (Saunders's Gull) |
| | *Melanitta fusca* (Velvet scoter) |
| Amphibians | *Caretta* |
| | *Chelonia mydas* |
| | *Dermochelys coriacea* |
| | *Eretmochelys imbricata* |
| | *Lepidochelys olivacea* |
| | *Natator depressus* |

Spatiotemporally, phenomenon 9 is one of the most dominant and influential land–sea connectivity. It is a long-term geomorphological process, such as in the Yangtze and Yellow river deltas in China, whose magnitude and development speed mainly depend on relationships among water discharge, river sediment concentration, and estuarine hydrodynamic conditions (Chen and Zong 1998; Shi et al. 2003). Usually, the greater the sediment flow from rivers, the faster a delta develops. By contrast, the less the sediment flow from upper reaches, the slower the delta develops; coastal erosion is even possible.

To elucidate the behavioral or functional connectivity of species by means of daily movement foraging, seasonal migration, feeding or breeding migration behavior, we recommend a number of species worthy of in-depth study (Table 3).

Above all, land–sea ecological connectivity refers to the interaction (convenience or hindrance) of physical, chemical, or biological processes between different terrestrial and marine ecosystems. Accordingly, it should be categorized into two types, behavioral (functional) connectivity and bio-geochemical (process) connectivity. The former is mainly caused by migration and/or foraging of neritic animals (e.g., birds and fish), and the latter is mainly produced by river nutrient transport (e.g., saltwater intrusion and delta development). Connectivity is also influenced by temporal factors. This type of connectivity, which depends on hydrologic cycle change, is referred to by some scholars as intermittent or seasonal connectivity, which differs from perennial connectivity.

### Analysis of land–sea ecological connectivity

Various methods have been developed and used to study ecological connectivity. Appropriate methods should be chosen according to local conditions, specific type of connectivity, and influential factors on land–sea ecological connectivity. Research into ecological connectivity includes two steps. First is identification of the existence, category and influential factors of land–sea ecological connectivity. Second is quantitative characterization and calculation of that connectivity.

Land–sea ecological connectivity is affected by several factors, which can be divided into two fundamental categories, natural and artificial. Natural factors mainly include topography, vegetation cover, climate and coastal hydrology, and involve various aspects. Artificial factors mainly include land-use change, construction of river dams, industrial pollution discharge, and fishery activities. In the identification and analysis of resistance factors of connectivity, site-specific conditions should be considered, especially for unique natural and artificial factors. Paris and Chérubin (2008) emphasized this basic principle in the discussion of river-reef connectivity in the Central America area. Their research confirmed a close relationship among land use, riverine water, sediment flux and coral reef areas, which demonstrated land–sea ecological connectivity. Moreover, seasonal sediment flux data of the major countries in the area show that river-reef connectivity is weakest in the dry season (October–December) and strongest in the wet season (April–June). Riverine water and sediment flux act as a resistance factor of connectivity in the dry season and promoting factor in the wet season, respectively. These phenomena lead to strong spatial and temporal differences in the coral reef ecosystem of the Caribbean coast.

The second stage of connectivity analysis selects and calculates a suitable connectivity index. At present, various connectivity indices, which are categorized as structural and functional, have been developed and widely used (Rodriguez Gonzalez et al. 2008; Ng et al. 2013). Structural connectivity indices include fragmentation, concentration, contagion and separation degree (Munroe et al. 2005). Many scholars generally use structural connectivity indices to reflect situations of land rectification and land use. For example, Singh et al. (2017) used fragmentation and spatial concentration indices to assess forest cover change and spatial dynamics of deforestation in Assam, India. Munroe et al. (2005) used a fragmentation and contagion indices to analyze changes in ecological connectivity in the landscape near Bloomington, Indiana, where agriculture and forest land retreated in the face of urban and suburban development.

The "average flow rate" index is used to assess the impacts of land–sea connectivity on global freshwater fish diversity (Liermann et al. 2012). Patch isolation metrics have proven to be more effective in predicting and reflecting the exercise capacity of organisms than the more commonly used distance-based metrics (Bender et al. 2003; Tischendorf et al. 2003; Ng et al. 2013; Niemandt and Greve 2016). Graph theory is used to identify least-cost paths between patches for focal organisms and to interpret the role of a landscape matrix in the context of landscape connectivity (Forman 1995; Urban and Keitt 2001; Correa Ayram et al. 2014). For a focal species dispersal probability model based on circuit theory, resistance has been used to identify all possible routes among habitat patches (McRae et al. 2008; Epps et al. 2011; Correa Ayram et al. 2014). Data/frame theory is used to quantitatively describe connectivity based on indices such as nearest-neighbor distance (Bender et al. 2003), spatial pattern indices (Urban and Keitt 2001; McGarigal et al. 2002; Moilanen and Nieminen 2002), and dispersal rates (Calabrese and Fagan 2004).

Overall, structural connectivity simply reflects the physical continuity of the landscape in geographic space, but does not indicate the functional connectivity of the landscape. Functional connectivity represents the degree to which the landscape promotes or hinders ecological processes, but it is difficult to observe and quantitatively calculate. Some complicated mathematical and statistical formulas and models have been used to calculate functional connectivity. For example, the index of possibility of connectivity (Saura and Pascual-Hortal 2007; Ng et al. 2013) was calculated to describe "the probability of two animals randomly placed within the landscape fall into habitat areas that are reachable from each other (interconnected)". In addition, the networked software Artificial Intelligence for Ecosystem Services ( http://www.ariesonline.org/) was developed to map natural capital, natural processes, human beneficiaries, and service flows to society. This model can be used to calculate multiple ecosystem services based on a connectivity paradigm (Mitchell et al. 2013).

## Applications of land–sea ecological connectivity

Research on land–sea ecological connectivity will be helpful to biodiversity preservation, ecosystem function maintenance, ecosystem services conservation and sustainable use, and wise management in coastal areas.

### Land–sea ecological connectivity and biodiversity

Over half a century, owing to the increasing frequency of extreme weather and intensification of human activities, 19% of the original area of coral reefs (Wilkinson 2008) and 35% of mangroves (Valiela et al. 2001) have been lost worldwide. Given this circumstance, to maintain and promote diversity of habitats and species on land and sea in coastal zones, some developed countries, such as Japan, Canada and Australia, have attempted to preserve and improve ecological connectivity among patches or habitats in terms of spatial scale (McRae et al. 2008; Department of the Environment, Water, Heritage and the Arts 2009; Environment Canada 2009). Moreover, academic institutions and universities in the United States and United Kingdom initiated several thematic projects to facilitate research into marine ecological connectivity, e.g., the research project "Coral Ecosystem Connectivity 2013: From Pulley Ridge to the Florida Keys" by the National Oceanic and Atmospheric Administration, USA (http://oceanexplorer.noaa.gov/explorations/13pulleyridge/welcome.html). In addition, remarkable progress that may greatly enhance practices of conservation and management has been made by researchers, for example, Buelow and Sheaves (2015) published "A birds-eye view of biological connectivity in mangrove systems," in which they pointed out that the following. Birds' daily moving foraging and seasonal migration can enhance functional connectivity among different mangrove ecosystems in coastal areas, and the prevention of fragmentation of mangrove habitat is important to maintain land–sea ecological connectivity. In a case study of araucaria forest and grassland around the Passo Fundo National Forest of southern Brazil, Carla Scariot et al. (2015) addressed the importance of establishing protected areas, buffer zones and legislation, by comparing fragmentation characteristics and vegetation loss in 1986, 1997 and 2010. Regarding river hydrologic connectivity, Covino (2017) minutely analyzed habitat of the biota in streams on the basis of ecological connectivity. He suggested that to improve the hydrologic connectivity, it is better to restore the ecological environment from the perspective of biological habitat.

### Land–sea ecological connectivity and ecosystem services

Land–sea ecological connectivity has a significant impact on the diversity and intensity of ecosystem functions and services, especially for coastal ecosystems connecting land and ocean, such as estuaries, mangroves, and tidal flats. (Barbier et al. 2011; Mitchell et al. 2013). In recent years, with economic and social development, both officials and the public have devoted more attention to the quality of the natural environment surrounding them. As a result, in ecological research and practical applications of land–sea ecological connectivity theory, whether it be structural (Pirnat and Hladnik 2016) or functional connectivity, connectivity has gradually become an important index to measure and evaluate ecosystem services (Pinoa and Marull 2012), and has been used in various fields and sectors, as follows.

In the economic and social fields, ecological connectivity has a wide range of applications. Commercial fishing has taken advantage of knowledge of fish migration, the marine food web and ecological connectivity among different marine habitats (Meynecke et al. 2008). In tourist areas, especially artificial or semi-natural scenic spots, ecological connectivity has been emphasized as one of the basic principles of landscape design and planning, as well as tour route design, toward improving recreation services of the ecosystem and attracting more tourists (Van der Zee 1990), At a more macro spatial scale, there is a universal phenomenon in which ecosystem services produced in some places (supply side) will be consumed in others (demand side), whose connectivity comes into being via trade and commerce. This in turn has profound feedbacks on trade, commerce and ecosystem services (Paetzold et al. 2010; Burkhard et al. 2012), e.g., the shaping or reshaping of ecosystem spatial patterns at macro spatial scale.

From the perspective of estuarine ecosystem connectivity, water and sediment regulation of the Yellow River is a very typical case. Zhang et al. (2016) showed an important connectivity between plant cover in the middle and upper reaches of the Yellow River and downstream sediment deposition and changes in wetland area in the estuary delta. This strongly affected water supply, flood regulation, and habitat services in the estuarine area. Therefore, in terms of Yellow River water and sediment regulation, we should start from various aspects and fields, in particular, the establishment of a comprehensive water and sediment control system within the entire river basin rather than within a section.

From the standpoint of landscape connectivity optimization, Mitchell et al. (2013) confirmed that with the decrease of landscape connectivity, ecosystem services clearly decline. Zang et al. (2017) analyzed the effects of land-use change on wetland landscape connectivity and ecosystem service in Yancheng National Nature Reserve of Jiangsu, China. They showed that increased human activities had markedly reduced landscape connectivity between shoal patch and *Phragmites australis* community wetlands, consequently attenuating the ecological function and service in coastal wetland dramatically.

## Relationships between human activities and land–sea ecological connectivity

Estuary and coastal zones are focal areas of land–sea interaction, where a variety of physical, chemical, biological and geological processes are intertwined and mutually interacting, making for a sensitive and fragile ecological environment. From a global perspective, estuary and coastal zones are also key areas of population agglomeration and marine resource utilization, with about 60% of the population and 2/3 of the large and medium-sized cities of the world (Lü et al. 2016). With the rapid development of urbanization and industrialization in estuary area and coastal zone, the impact of human activities on ecosystems is increasing. The original land–sea connectivity has been seriously disturbed, destroyed or altered. Research has indicated that almost all marine ecosystems have been influenced by human activities, and 41% of marine ecosystems have been influenced by multiple factors (Halpern et al. 2008). At the same time, with the deterioration of coastal environments and ecosystems, the sustainable development of the urban, industrial, agricultural, and service sectors in coastal areas has also faced serious challenges.

## Impacts of intensifying human activities on land–sea ecological connectivity

Human activities that have major impacts on land–sea ecological connectivity mainly include excessive land-use and unreasonable land-cover change in land and coastal areas, large-scale riparian and coastal engineering construction, and serious pollution caused by massive urban expansion and industrialization in coastal areas (Crook et al. 2015).

### *Excessive land use*

Excessive land use in coastal zones is marked by excessive wetland reclamation and accelerated urban expansion in many countries. Irrational and excessive wetland reclamation can result in serious loss of migratory fish spawning grounds, breeding grounds and bird habitats, and block connectivity among organisms. Furthermore, wetland loss and fragmentation reduce the connectivity between land and sea. Wetland reclamation in the coastal zone of Yancheng, a coastal county in Jiangsu Province of China, is a representative case. In this area, Zhai et al. (2009) and Gu et al. (2012) studied the spatiotemporal characteristics of land use/cover change and its impacts on wetland ecosystems, respectively. They obtained similar results and conclusions as follows: (1) dominant communities and categories of plants in the wetland were *Suaeda salsa, Spartina alterniflora* and *Phragmites australis*; (2) mainly because of human activities over recent decades, the landscape changed dramatically, with a large area of natural landscape being replaced by artificial landscape; specifically, *Suaeda salsa* and *Phragmites australis* communities have witnessed the largest reductions in area, and most of the disappeared wetland changed into aquaculture ponds and farmland area; (3) the rapid expansion of artificial landscape greatly reduced natural wetland, directly resulting in the loss of fish spawning and breeding grounds and disrupting the functional connectivity of biological life cycles; furthermore, a remarkable loss of intertidal mudflats greatly damaged the functional connectivity at intercontinental scale because coastal wetland in Yancheng is one of the important stops on the migration route of eastern Asia–Australia birds (Xia et al. 2017).

### *Large-scale engineering construction*

Large-scale construction projects, such as river water conservancy, reclamation and offshore infrastructure, plus coastal mining have had various negative impacts on land–sea ecological connectivity.

Hydraulic engineering could have more extensive or remarkable impacts on land–sea ecological connectivity, because it has direct or indirect and irreversible effects on river sediment flux and its seasonal distribution. With the decrease of sediment flux in an estuary, the growth of delta and wetland in the estuarine area slows or even begins to shrink. In addition, coastal erosion has become one of the main issues of coastal zones in the world, and has been exacerbated by increased hydraulic engineering in the upstream of seagoing rivers. By analyzing sediment flux changes in the Nile River before and after the construction of Aswan Dam, Morcos Fanos (1995) stated that the amount of sediment discharged into the Mediterranean had decreased by 98%. By analyzing changes in sediment carried into the sea by the Yangtze River and the balance of deposition versus erosion areas of the estuary, Dai et al. (2016) showed that Three Gorges Reservoir has aggravated the reduction of Yangtze River sediment flux into the sea, and the rapid decrease of sediment flux upgraded the dominant reason for the shift from siltation to erosion in the estuary delta.

Reclamation projects mainly include land reclamation, artificial island construction, and the construction of ports, docks, seawalls, trestle bridges, and sea-crossing bridges. Although sea reclamation is an effective means to relieve conflicts of land use among industry, agriculture and urban development, inappropriate and excessive reclamation upsets the balance of coastal nutrient circulation, disrupts or destroys coastal ecosystems, disturbs functional connectivity of the involved ecosystems, and ultimately leads to a series of marine environmental disasters, such as local water pollutant enrichment and harmful algae outbreaks. Kim and Park (2017) stated that in the sea area around the Koreas Saemangeum Project, there was a dense relationship between a red tide outbreak during two consecutive years and the reclamation works. The reclamation project will permanently alter the original coastline and seawater chemical environment, altering the pattern and process of coastal erosion–sedimentation, changing nearshore hydrodynamic conditions, disturbing original connectivity between sea surface and seabed, and ultimately modifying the food chain and collective death of seabed organisms. For example, by researching the benthic biocenose of reclamation areas in the Yangtze River estuary of China, Wu et al. (2005) found that because of the implementation of the reclamation project, the diversity and density of marine life decreased considerably. In addition, the reclamation project will block physical and biological connectivity between adjacent sea and coastal wetland, thereby greatly influencing coastal wetland and landscape structures. Han et al. (2006) studied the change of coastal wetland in southern China, indicating that large-scale and unreasonable sea reclamation was one of the most important reasons for mangrove wetland degradation.

### *Serious pollution caused by massive urban expansion and industrialization*

In recent decades, with the acceleration of coastal urbanization, industrialization and modernization of agriculture, increased pollutants have been discharged into the air, rivers, lakes and ocean. At present, serious water pollution in coastal areas brought about by the massive urban expansion and industrialization includes heavy metal pollution, eutrophication, plastic waste, and petroleum hydrocarbon pollution (Lü et al. 2016). Driven by various natural factors such as river runoff and atmospheric circulation, and multiple artificial factors such as groundwater discharge and anthropogenic discharge, numerous pollutants have been discharged into offshore waters. Estuaries and enclosed bays rank as the worst areas in terms of water pollution, where, the habitat quality of local and migratory species has suffered great damage, and the feeding migration and breeding migration of some species between land and sea were blocked. The US Environmental Protection Agency has stated that Cu and Pb are the most serious metal pollutants in the world. Moulay Bousselham Lake in Morocco (Africa) and Bremen Bay (Germany) have the most serious water pollution in the world (Lü et al. 2016). Regarding China, Ni, Cr and Zn concentrations in waters surrounding the Shandong Peninsula, and Hg, As and Pb in Liaodong Bay are very high, but water environment pollution around Hainan Island and the Yangtze River Delta is slight (Hu et al. 2013a, b; Li et al. 2013; Wang et al. 2014; Lü et al. 2016).

Eutrophication in terrestrial rivers, lakes and coastal waters mainly comes from agriculture (fertilizers and pesticides), animal husbandry, aquaculture, industrial waste water, waste residue, and other wastes. Nitrogen and phosphorus elements transported into coastal waters from land-based sources of water tripled from the 1970s to 1990s. Excessive discharge provides sufficient nutrients for the growth of algae in coastal waters. With the explosive propagation of algae, the biodiversity, water quality, water transparency and oxygen content in coastal waters has declined significantly, breaking the balance of ecological connectivity in coastal waters and leading to large numbers of abnormal biological deaths, pathogen invasion, and exotic species invasion (Sherman 2014). It has been reported that the number of hypoxic areas in coastal waters has exceeded 400 worldwide, covering more than 245,000 km$^2$ (Doney 2010; STAP 2011), and the number of hypoxic areas were increasing rapidly, with an annual growth rate of 5.54% (Vaquer-Sunyer and Duarte 2008).

Very similar to seawater eutrophication, because of climate change and human discharges, marine garbage (especially plastic pollution) has gradually become one a focus in coastal countries around the world. Most of the marine garbage is plastic waste, widely distributed on the ocean surface and seabed, and along the coastline (Lavender Law and Thompson 2014; Obbard et al. 2014). It was estimated that in 2010, plastic waste generated in 192 coastal countries amounted to 275 million metric tons (MT), and 4.8–12.7 million MT has entered the ocean (Jambeck et al. 2015). With the gradual accumulation and fragmentation of marine floating garbage, the landscape, structural and functional connectivity among coastal patches will weaken or even disappear completely.

## Importance of land–sea ecological connectivity maintaining human society

In summary, various human activities in coastal areas have promoted social and economic development; however, they have also had a number of negative impacts and are disturbing or changing the balance of material cycles and energy flows among land, sea and atmosphere in coastal zones. This disturbs land–sea ecological connectivity. At the same time, the safety of human activities, lives and properties, as well as the sustainability of social and economic development, are declining with the weakening and destruction of land–sea ecological connectivity. This is characterized by the intensification of coastal natural disasters, increased vulnerabilities of the human living environment, and degradation of coastal ecosystem services. For example, uncontrolled construction of dams, reservoirs and other water and soil conservation facilities on a river and its tributaries will substantially reduce river runoff, and underground water resources in lower reaches and coastal areas will lack supplementation. This will inevitably result in underground water lowering and seawater intrusion into coastal areas. This intrusion in coastal areas of Laizhou Bay, China was observed in the 1960s for the first time. In the early stages, there were a large number of dams and riverbanks in the upper reaches of rivers, as well as sea reclamation in the estuarine and coastal area that resulted in rivers drying up, underground water lowering, and seawater intrusion. Then, beginning in the 1980s in this area, excessive groundwater exploitation has gradually become the dominant reason for salt water intrusion. As a result, land area suffering salt water intrusion amounted to 1773.6 km$^2$ in 2002 (Wu et al. 2008). Such serious salt water intrusion has aggravated soil salinization, productivity decrease of farmland, drinking water crises, and human diseases such as dental fluorosis, osteofluorosis and nodular goiter in the area.

Unreasonable exploitation of offshore minerals can also disturb or destroy the ecological connectivity of coastal zones, leading to a series of catastrophic consequences that endanger the lives and properties of coastal residents. Xu et al. (2015) asserted that in the northern coastal areas of Shandong Province, China, water depth near the shoal increased continuously, mainly because of disorderly sand mining activities. This in turn disturbed the coastal hydrodynamic environment, breaking the balance between erosion and deposition, exacerbating coastal erosion, and producing land loss, collapse or flooding of coastal buildings and great economic loss.

Serious pollution caused by massive urban expansion and industrialization not only changes the balance of nutrient cycling in coastal waters but also destroys the functional connectivity between land and sea. Furthermore, harmful algae outbreaks and the expansion of oceanic anoxic areas caused by seawater eutrophication have powerful negative effects on human offshore economic activities such as offshore fisheries and tourism. For example, the economic cost of the *Ulva prolifera* bloom at China's 2008 Olympic sailing venue amounted to 592.657 million CNY (Wang et al. 2009). Marine waste and pollutants ingested by marine animals are transmitted and enriched by the food chain, which affects the quality of marine fishery products and endangers human food safety and health, because of their toxic effects (Rochman et al. 2013; Lü et al. 2016; Pelorosso et al. 2016).

## Conclusions and perspective

This paper focuses on land–sea ecological connectivity. By discussing its basic concepts, representative phenomena, analysis methods, applications, and relationship to human activities, we drew the following conclusions.

In general, land–sea ecological connectivity is the relationship between terrestrial and marine ecosystems, via biological migration, hydrologic cycling, nutrient transport, and climatic processes. It enriches coastal ecosystems at scales from individual organisms to global, which supports the sustainability of biodiversity and ecosystem services and contributes to human wellbeing.

Land–sea ecological connectivity in a region varies with changes in multiple physical and artificial factors, such as climate, land cover, biotic community and human activities. Structurally connected habitat patches are not always functionally connected, whereas structurally unconnected patches may be functionally connected owing to the movement of species. Different types of land–sea ecological connectivity are scale-variable, occupying different temporal ranges from seconds to century, and covering spatial ranges from individual organism to global.

Human activities such as land use, engineering construction, urbanization and industrialization have continuously increased and imposed irreversible disturbance and destruction on land–sea ecological connectivity, thereby threatening biodiversity and ecosystem services at various temporal and spatial scales. Hence, achievements of theoretical research and practical experiences in ecological connectivity should be fully applied in coastal areas to maintain and restore the land–sea ecological connectivity and remedy various problems that arise from blocking and damaging of ecosystem services. For example, the maintenance and restoration of land–sea ecological connectivity should be assigned great importance and priority during monitoring, management and legislation in estuarine and coastal management, as well as in offshore biodiversity conservation.

Land–sea ecological connectivity is characterized by complexity, dynamics and regionalism. The coastal zone is the key and core area of this connectivity, so it is critical to strengthen continuous academic research focused on this connectivity in coastal areas. Based on analyzing the connectivity of water, sediment, nutrients and energy among various habitats and ecosystems in estuarine and coastal areas, a clearer picture will be gained of the characteristics, intensity and interactions between land–sea ecological connectivity and ecosystem functions and services. Then, with further investigation of the critical controlling factors, regulatory mechanisms and effective measures of land–sea ecological connectivity maintenance, comprehensive observation and systematic studies of that connectivity across scales will be established. These studies will promote the conservation of biodiversity, maintenance and enhancement of ecosystem functions and services, and improvement of socioeconomic sustainability in coastal areas or larger areas of land and sea.

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