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Sea-Islandscape Ecology: An Integrated Perspective for the Conservation and Management of Sea Islands

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Abstract

With vigorous development of marine economies, sea islands have been the frontiers of marine exploration. Degradation of sea-island ecosystems is pervasive, and conservation and management of sea islands is increasingly urgent. Landscape ecology provides an ideal theoretical framework for the conservation and management of sea islands at ecosystem level. A new concept, "sea-islandscape ecology", was developed based on landscape ecology. To address the urgent problems related to sea islands, the paper explores the following five potential applications of sea-islandscape ecology: (1) noninvasive investigation and assessment of uninhabited sea islands; (2) variation in sea-islandscape ecosystems at different latitudes; (3) mechanisms of anthropogenic disturbances to sea-islandscape ecosystems; (4) coupling sea-islandscape pattern changes with ecological processes; (5) ecological integrity (EI) of sea-islandscape ecosystems.

Keywords: Sea-islandscape ecology; Sea islands; Ecological integrity; Conservation and managementy

Introduction

Sea islands are naturally formed areas of land that are surrounded by sea water and are above the sea level at high tide. While the sea islands of the world are hugely diverse, they are isolated, geographically well-defined, and have distinct boundaries [1]. These characteristics allow highly self-governed ecological processes and the formation of uniquely evolved biota. Consequently, sea islands have greatly inspired scientific interest, and have long been used as model systems for research into evolution, biogeography, ecology, and conservation [2-3]. The isolation and small size of sea islands make them good cases for studies of biodiversity, and the sensitivity of their biota makes them important subjects of extinction studies [4]. A considerable number of ideas and methods from sea-island research have contributed to the creation and development of many disciplines and their core theories [5-7].

Sea islands provide important habitats for animals and plants, and undertake multiple ecological functions. One in six of the earth's known plant species occur on sea islands [8], and many sea islands are considered to be biodiversity "hot spots" in global terms [9]. The isolation of sea islands often leads to a high level of plant and animal specializations that are associated with high rates of endemism [2]. For instance, more than 80% of the vascular plants on Saint Helena and the Hawaiian Islands are endemic to those islands [10]. Some inhabited sea islands, such as Xiushan Island, Jintang Island in Zhejiang province, China, supply natural fresh water and agricultural products to local islanders. In the Pacific, the most sea islands have welcomed tourism, and offered recreational, sightseeing, and cultural services to visitors from around the world [11]. With further development of sea-island land, industrial projects, like shipbuilding, harbours, waste disposal, are increasingly placed on sea islands [12]. In China, wind farm are placed on many sea islands, such as Tantoushan Island in Zhejiang Province, Nan'ao Island in Guangdong Province.

Meanwhile, landscape ecosystems of sea islands are undergoing tremendous changes due to natural and anthropogenic causes. Community fluctuations in sea islands, and even sea-island ecosystem degradation, are often the direct result of natural disasters, such as tsunami and extreme climate [13]. Especially, anthropogenic disturbances play a significant role in the changes of sea-island landscape ecosystems. Various anthropogenic activities have greatly changed the geomorphology, hydrology, animal communities, and plant communities of Christmas Island and Cocos Island in the eastern Indian Ocean [14]. Hundreds of species have been driven to extinction or extirpation since human settlement on the Caribbean Islands approximately 6000–7000 year ago [15]. Tourism development on sea islands in the Pacific have resulted in a number of environmental and ecological problems, such as environmental degradation and pollution, destruction of habitats, damage to ecosystems, and the loss of coastal and marine resources [16].

Therefore, sustainable development of sea islands is becoming an increasingly serious concern. Conservation and management strategies that are specifically designed for sea islands are urgently needed. An understanding of the status and ecological processes of sea islands is a prerequisite for these strategies, and require the appropriate theoretical framework. Landscape ecology provides a potential theoretical framework for conservation and management of sea islands that includes both the biophysical and pattern-process perspective and the holistic and humanistic perspective [17].

Combining landscape ecology theory and its application to sea islands has resulted in the development of a new concept called "sea-islandscape ecology." To address the urgent problems related to sea islands, it is necessary to explore the following five potential applications of sea-islandscape ecology: (1) noninvasive investigation and assessment of uninhabited sea islands; (2) variation in sea-islandscape ecosystems at different latitudes; (3) mechanisms of anthropogenic disturbances to sea-islandscape ecosystems; (4) coupling sea-islandscape pattern changes with ecological processes; and (5) ecological integrity (EI) of sea-islandscape ecosystems.

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Landscape and landscape ecology

There are many interpretations of "landscape" and no uniform definition has been adopted. The definition most often used in scientific research was provided by Forman and Godron [18], who considered landscapes as heterogeneous land areas composed of a cluster of interacting ecosystems that are repeated in similar form throughout. As used in this definition, ecosystems are the physical, chemical, ecological, and geographical entities that integrate all natural and human patterns and processes, and equate to the patch mosaics of landscape ecology. The roots of landscape ecology can be traced back to the mid-nineteenth century with the introduction of "landscape" as a scientific term by the explorer-geographer Alexander von Humboldt [19]. Based on von Humboldt's work, Passarge proposed "landscape science" as a new subfield of geography in 1919 [20]. Following the scientific concept of "ecosystems" that was proposed by Tansley in 1935 [21], German biogeographer Troll formally coined the term "Landscape ecology" in 1939 [22].

Since its emergence, landscape ecology has aroused the strong interest of many scholars and has been applied to various fields, such as biological conservation [23], forest park design [24], eco-environmental impact assessment [25], wetland studies [26], sound studies [27-28], sustainable development, and marine science [29,30]. A series of corresponding sub-disciplines have emerged, including soundscape ecology [31], forest landscape ecology [24], seascape ecology [30,32], and waterscape ecology [33]. Theoretically, the number of potential sub-disciplines depends on the number of patch types that exist at some scale, and there is a tendency to divide landscape ecology too finely and extend it too widely.

Heterogeneity concisely and precisely captures much of the essence of landscape ecology [34]. Based on heterogeneity, the units of landscape structure can be classified as patch, corridor, or matrix [18]. Corridors are often viewed as a kind of special patch. Therefore, landscape structure could be simplified to include only patches and matrices. There is no doubt that water and land are the two main patch or matrix types. Based on different assemblages of patches and matrices, landscape ecology can be subdivided into four sub-fields: terrestrial landscape ecology (land patches in land matrices; Figure 1a), river and lake landscape ecology (water patches in land matrices; Figure 1b), and islandscape ecology (land patches in water matrices; Figure 1c), seascape ecology (water patches in water matrices; Figure 1d). Islands consist of sea islands and freshwater islands depending on whether matrices are seawater or not. The following parts are concerned exclusively with sea-islandscape ecology.

Sea-islandscape ecology

Definition of sea islands in sea-islandscape ecology: Article 121 of United Nations Convention on the Law of the Sea defined a sea island as a naturally formed area of land, surrounded by water, which is above water at high tide. The category of sea islands is very broad, and it is difficult to determine which lands are not or have never been sea islands. In terms of size, the distinction between a continent and an island is fuzzy. Size gap method might provide an objective definition of what are the mainlands of the world archipelago compared to other land that usage tends to consider as islands per se [35]. Antarctica and Greenland are not strictly emergent land because they are mostly ice caps with most of their bedrock below sea level. In view of this, the largest size gap appears between Australia and New Guinea, and New Guinea is the largest sea island. Sea islands in sea-islandscape ecology are naturally formed lands with area less than 1,000,000 km^2, surrounded by seawater, which is above water at high tide. Furthermore, the focus of sea-islandscape is smaller sea islands. In addition, there are narrow, middle and broad definitions of sea-islandscape ecosystem regions: the narrow definition includes only sea-island lands in sea-islandscape ecosystems; the middle definition includes both sea-island lands and intertidal zones in sea-islandscape ecosystems; and the broad definition includes sea-island lands, intertidal zones, and coastal waters in sea-islandscape ecosystems (Figure 2). Here, we will use the middle definition.

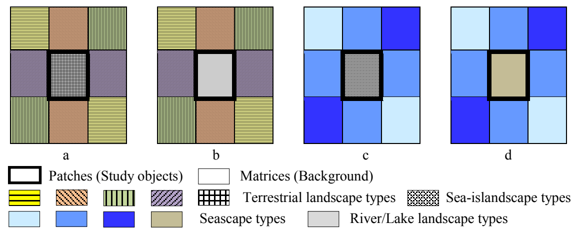

Figure 1: Sub-fields of landscape ecology based on different assemblies of patches and matrices.

Classification of sea islands: As far as classification of sea islands is concerned, it was fully discussed in the works 'A WORLD of ISLANDS: *An Island Studies Reader*' [35]. There are two kinds of classification schemes for sea islands that are based on the natural and social attributes (Table 1). In terms of natural attributes, sea islands are divided into three types according to their geological origin and biological properties [36]: oceanic islands, continental islands, and continental fragments. The spatial location of sea islands in relation to the Earth's plates [37], the distance to continents [35], generation types [38], and material composition have all been used as classification bases. On the other hand, the social attributes are used as the basis of classification. One such classification scheme divided sea islands into uninhabited islands and inhabited islands [39]. Sea islands are also divided into state-level, province-level, municipal level, county-level, township-level and village-level islands [40].

The classifications of sea islands based on natural attributes, to some extent, reflect the origins of sea islands or the succession processes and stages of sea-islandscape ecosystems, while the classifications based on social attributes are the need of management of sea islands. As an applied subject, sea-islandscape ecology aims to promote comprehensive conservation and management of sea islands. The study on the interaction between human and sea-islandscape ecosystem is the core of sea-islandscape ecology. Ecosystems can be divided into natural, semi-natural and highly modified ecosystems according to the degree of anthropogenic disturbance. Based on this idea, the paper divided sea islands into urban-type sea islands, rural-type sea islands, uninhabited sea islands (Table 2). Suffered a great modification, urban-type sea islands are the sea islands that contain the township and above government residents and are oriented in industry and trade and business. Rural-type sea islands are those islands with the only agriculture. Uninhabited sea islands are the sea islands without any inhabitants. Conservation and management of sea islands are different with the different sea-island types.

Progress in sea-islandscape ecology: Although this paper is the first to define the scientific term "sea-islandscape ecology," research pertaining to it has been conducted since people first became concerned about sea islands. Darwin who engaged in comparative research of the bird landscape between the Galapagos Islands and the mainland of South Africa, could be called as the grandfather of sea-islandscape

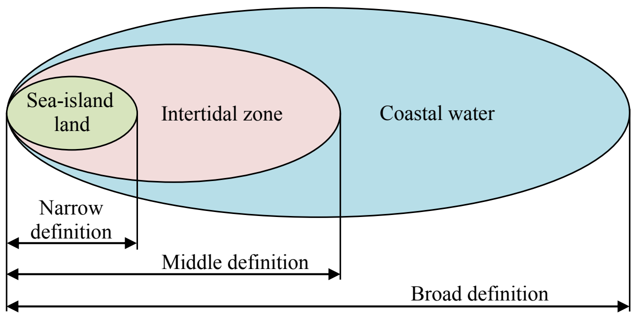

Figure 2: Sketch map of definitions of sea-islandscape ecosystem.

ecology. Since then, sea islands have been used as model systems for research into evolution, biogeography, ecology, and conservation [2]. The number of sea-islandscape ecology studies has increased rapidly in recent decades.

The impacts of natural hazards on sea-islandscape patterns are an important part of sea-islandscape ecology. Studies of these impacts include the impact of tsunamis on the coastal ecosystems [13,41], the impacts of storm cyclones on mangrove forests [42], and the impacts of earthquakes on forests [43]. Natural hazards are often accidental events, but recently, there has been an increase in their frequency. The impacts of natural hazards on sea-islandscapes are usually holistic rather than partial. However, current studies are mainly focused on the impacts of natural hazards on sea-islandscape patches rather than whole sea-islandscape ecosystems.

Sea-islandscape pattern changes resulting from anthropogenic disturbances are another part of sea-islandscape ecology. Anthropogenic activities are the major causes of disturbances to sea-islandscape ecosystems, especially on inhabited sea islands. Human settlement and concomitant productive activities greatly change sea-islandscape types and patterns. Examples of this type of change can be found on Christmas Island and Cocos Island in the eastern Indian Ocean [14] and Meizhou Island in Fujian Province, China [44]. Occasionally, the shapes of sea islands are altered [45]. Tourism development further extends the anthropogenic impacts on sea-islandscape ecosystems [16,46-49]. Increasing population may result in the over-abstraction of sea-island freshwater and to water contamination from pesticide and fertilizer use, poor sanitation, and leaching from solid waste [50]. On many islands, invasive species have caused tremendous ecological and economic damage and high social costs [51,52]. Sea-islandscape ecosystems are also deeply affected by climate change, which is mainly caused by human-induced alterations of the natural world. As precipitation and temperature patterns change, forests will become more susceptible to invasive species, disease or fire. This may lead to broad landscape shifts or a complete loss of habitat. Mechanisms of anthropogenic disturbances to sea-islandscape ecosystems and temporal and spatial prediction of their developmental trends should be discussed as part of implementing reasonable conservation and integrated management strategies for sea islands.

The ecological restoration of sea islands have become a new area of study in sea-islandscape ecology that is focused on ways to diminish or remove adverse impacts caused by natural and anthropogenic causes. It was suggested that ecological restoration of sea islands should take into account terrestrial, coastal, and offshore subsystems from a holistic perspective [53]. So far, restoration of sea islands is still at the

Classification bases	Types of sea islands	References
Geological origin Biological properties	**Continental islands** **Continental fragments** **Oceanic islands** Volcanic islands Reef islands	Wallance, 2007 Whittaker and Fernández-Palacios, 2007
Location relationship of sea islands and the Earth's plates	**Plate boundary islands** Islands at divergent plate boundaries Islands at convergent plate boundaries Islands along transverse plate boundaries **Intra-plate islands** Linear groups of islands Clustered groups of islands Isolated islands	Nunn, 1994
Proximity to continents	**Pericontinental isalnds** **Open sea islands**	Depraetere and Dahl, 2007
Generation types	**Continental islands** **Alluvial islands** **Oceanic islands** Volcanic islands Reef islands	Yang, 2000
Material composition	**Rock islands** **Sand and mud islands** **Reef islands**	State comprehensive survey group of sea island resources, 1996
Area	**Super-large islands** (>2500km^2) **Large islands** (100～2500km^2) **Middle islands** (5～99km^2) **Small islands** (0.0005～4.9km^2)	State comprehensive survey group of sea island resources, 1996
Whether people settled	**Uninhabited islands** **Inhabited islands**	State comprehensive survey group of sea island resources, 1996
Administrative levels	**State-level islands** **Province-level islands** **Municipal level islands** **County-level islands** **Township-level islands** **Village-level islands**	Xia, 2012

Table 1: A summary of the current classification schemes of sea islands.

Classifications	Characteristics	Examples
Urban-type sea islands	Highly modified landscape ecosystems; the township and above government residents; oriented in industry and trade and business	Molokai island, USA Liuheng island, China
Rural-type sea islands	Semi-natural landscape ecosystems; usually village and below government residents, or natural village; oriented in agriculture, partially tourism development or natural preserve	René-Levasseur island, Canada Xiushan island, China
Uninhabited sea islands	Natural landscape ecosystems; no inhabitants	Ernst Thälmann island, Cuba Auckland Islands, New Zealand

Table 2: Classification of sea islands in sea-islandscape ecology.

fundamental exploration stage, and further research is needed in order to develop restoration theories and techniques.

Notwithstanding progress in sea-islandscape ecology, there is insufficient attention paid to sea-island integrity, dynamic changes in sea-islandscape ecosystem, and the mechanisms of sea-islandscape changes. Due to the isolation and limited buffer capacity, a holistic and ecosystem-based idea for conservation and management of sea islands is needed. As an applied science, sea-islandscape ecology provides a systematic framework for understanding the landscape changes and deep-seated ecological processes. Such a framework should form the foundation of reasonable conservation and integrated management of sea islands.

Prospective applications of sea-islandscape ecology

Noninvasive investigation and assessment of uninhabited sea islands: Noninvasive investigation and assessment is used to acquire information about sea-islandscape ecosystems without touching them. In many cases, anthropogenic destruction of sea-islandscape ecosystems starts with blind disturbances, including scientific investigations. Due to the special sensitivity and frangibility of sea-islandscape ecosystems, the disturbance starting point and subsequent pattern determine the effects that a given disturbance will have on sea-islandscape ecosystems. There are many uninhabited sea islands in the world, some of which might be exploited in the future. In China alone, 176 uninhabited sea islands were listed for exploitation in 2011. It makes sense to conduct noninvasive, pre-exploited investigations and assessments of sea islands that facilitate the formulation of reasonable disturbance schemes and, ultimately, reduce the adverse impacts of proposed disturbances on the sea-islandscape ecosystems.

Advances in remote sensing techniques provide the potential for noninvasive investigation and assessment. Multi-angle viewing, multi-spectral sensing, hyperspectral sensing, and radar can all be used as noninvasive methods of acquiring information about sea islands. This information can be used to evaluate characteristics of sea-island ecosystems at landscape level, including vegetation communities, land cover, hydrological characteristics, and topography. In order to minimize anthropogenic impacts on sea-islandscape ecosystems, decisions as to whether and how to exploit uninhabited sea islands can be made based on the results of noninvasive investigation and assessment. This application of sea-islandscape ecology can also be used to improve the effectiveness of sea-island field surveys, thereby reducing research costs.

Variations in sea-islandscape ecosystems at different latitudes: Latitude is one of the key factors affecting landscape ecosystems, and this relationship is generally referred to as the "latitudinal effect". The latitudinal effect is the combined outcome of variations in precipitation, solar radiation, heat, and other factors. Landscape ecosystems generally vary as a result of the latitudinal effect [54]. For example, forest landscapes tend to change with distance from the equator from tropical rainforests, to subtropical evergreen broadleaf forests, temperate deciduous broadleaf forests, and, boreal forests.

The latitudinal effect works similarly for sea-islandscape ecosystems. Variations in sea-islandscape ecosystems at different latitudes mainly include landscape types and patterns, species composition of patches, and ecological processes. Variations in uninhabited sea-islandscape ecosystems reflect the diversity of ecological successions under natural conditions, whereas those in inhabited sea-islandscape ecosystems result from the combined actions of anthropogenic disturbances and ecological successions at different latitudes. Temporal dynamics and spatial differentials should be considered in the conservation and management of sea islands. The latitudinal effect can be viewed as spatial variation of sea-islandscape ecosystems. Research into variations in sea-islandscape ecosystems will provide a foundation for the differential conservation and management of sea islands at different latitudes.

Mechanisms of anthropogenic disturbances to sea-islandscape ecosystems*:* There is no doubt that anthropogenic disturbances have resulted in widespread changes to sea-islandscape ecosystems. Disturbances can be divided into temporary and lasting disturbances based on duration. Sea-islandscape ecosystems might easily recover from temporary disturbances, including occasional surveys and temporary facilities. A majority of disturbances are lasting disturbances, including settlement, tourism exploitation, industrial development, invasion by human-induced alien species, and climate change. Once the cumulative or instantaneous intensity of lasting disturbances exceeds ecosystem resilience, sea-islandscape ecosystems slip toward irreversible degradation. Therefore, lasting disturbances are the main objects of research.

Research into mechanisms of anthropogenic disturbances to sea-islandscape ecosystems is comprised of the identification of the means of disturbance, measurement of disturbance intensity, and measurement of ecosystem response. Anthropogenic activities engenders various means of disturbance, such as the harvest of trees for fuel, modifications of coasts for ports, alterations of freshwater inflows, road construction, and conversion to residential or agricultural uses [55]. The intensity of disturbances and the ecosystem responses vary with the means of disturbance. Land-use changes cause changes to plant and animal habitats and to sea-islandscape patterns by direct modification of sea-islandscape types. The spatial characteristics of disturbances should also be included in studies of sea-islandscape ecology. Patches may differ in their sensitivity to disturbances. With continued disturbance, a disturbed area will tend toward stabilization and can be considered as a new sea islandscape patch, namely, a Disturbance Patch (DP). The shapes of DPs influence the length of the disturbance interface between DPs and other patches, known as the "shape effect" in landscape ecology. Complex DPs have longer interfaces than simple DPs, that cover the same area. Therefore, complex DPs might result in greater disturbances than simple DPs. Research into the mechanisms of anthropogenic disturbances to sea-islandscape ecosystems is helpful for understanding the relationship between the means of disturbance and sea-islandscape changes, as well as sea-islandscape ecosystem trends.

Coupling sea-islandscape pattern changes with ecological processes: The relationship between landscape pattern changes and ecological processes is one of the key topics of landscape ecology [53]. On the one hand, landscape pattern changes arise from ecological processes, and the pattern changes consequently provide clues about ecological processes. Knowledge of ecological processes could contribute to our understanding of the formative causes and change trends of landscape patterns. On the other hand, landscape pattern changes affect ecological processes. Ecological restoration is the repair of ecological processes by changing landscape patterns. However, instead of the existence of the relationship between landscape pattern changes and ecological processes, the current focus is to explore which patterns are related to which processes, correlations between patterns and processes, and how to regulate and control ecological processes [56]. Therefore, coupling landscape pattern changes with ecological processes through modeling become an important part of landscape ecology research.

Natural processes drive sea island succession and the formation of landscape matrices. Landscape pattern changes should first be coupled with natural ecological and physical geographic processes. These processes might include wildlife behavior, sedimentation processes, hydrological processes, soil erosion processes, and temporal and spatial variations in the water and nutrient content of soil. Anthropogenic processes increasingly dominate sea-islandscape pattern changes with the multifarious exploitation of sea islands, especially for tourism and economic growth. The emphasis on coupling sea-islandscape pattern changes with ecological processes includes consideration of anthropogenic processes, such as the encouragement and restraint of policies, direct patch changes, environmental pollution, human-induced alien species invasion, and human-induced heat island effects. In particular, freshwater resources of many sea islands are often very scarce, and are mainly supplied by rainfall. Landscape pattern changes can affect the freshwater supply of sea islands by the regulation of vegetation landscape on runoff. Therefore, it makes special sense to conduct a research on the effects of landscape pattern changes on sea-island hydrology. Additionally, the relationships between landscape pattern changes and ecological processes may be magnified in sea islands, as a result of their isolation and small size. Sea islands could be used as a model for coupling landscape pattern changes and ecological processes.

Ecological integrity of sea-islandscape ecosystems: Ecological Integrity (EI) was defined to include the following [57]: (1) ecosystem health, which might apply to some non-pristine or degraded ecosystems, provided that they function successfully; (2) the ability of ecosystems to regenerate themselves and withstand stress, especially non-anthropogenic stress; (3) the optimum capacity of ecosystems for undiminished developmental options; (4) the ability of ecosystems to continue undergoing change and development that is unconstrained by past or present human interruptions past or present. EI is a holistic approach to the measurement of ecosystem quality that allows for status assessment at ecosystem level, rather than just at species or chemical level alone. Such an integrative tool to assess ecosystem quality is very important for managers and decision makers. EI has become a central concept in environmental conservation and resource management. It makes sense to research sea-island EI with consideration of island isolation, size and limited buffer capacity.

Sea-island EI is comprised of physical, chemical, biological, and conscious elements. The physical elements are chiefly topographical and hydrological characteristics. The chemical elements consist of the types and concentrations of chemical substances in soil and water. The biological elements are the types, assemblages, and habitats of species, especially indicator species. The conscious elements are the perceptions and attitudes of islanders, exploiters and managers to EI. Research into the EI of sea-islandscape ecosystems is performed to identify indicators that represent sea-island EI and define the reference conditions for these indicators. Sea-island EI research helps to make clear what aspects of sea-island ecosystems should be monitored and the methods of monitoring them. Sea-island EI research also helps to quantify the objectives of conservation and management of sea islands (Figure 3).

In theory, there is an inverse correlation between EI and the cost of conservation and management of sea islands (Figure 4). Sea-island EI gradually declines with the duration of anthropogenic disturbances, whereas the corresponding cost of conservation and management grows rapidly. However, exploitation could not continue beyond the bottom line (EI_{min}) in any case. In addition, the quantification of ecosystem status and conservation objectives using EI permits the evaluation of sea-island conservation and management costs.

Conclusion

Sea islands have been the frontiers of marine exploration. Sea-islandscape ecosystems are undergoing various changes as a result of the development and utilization of sea islands. Reasonable conservation and integrated management strategies that are specifically designed for sea islands are urgently needed. Sea-islandscape ecology may provide a theoretical framework for these strategies. Sea-islandscape ecology research will contribute to improvement of the conservation and management of sea islands. Sea-islandscape ecology involves the noninvasive investigation and assessment of uninhabited sea islands, study of variations in sea-islandscape ecosystems at different latitudes, research into the mechanisms of anthropogenic disturbances to sea-islandscape ecosystems, coupling sea-islandscape pattern changes with

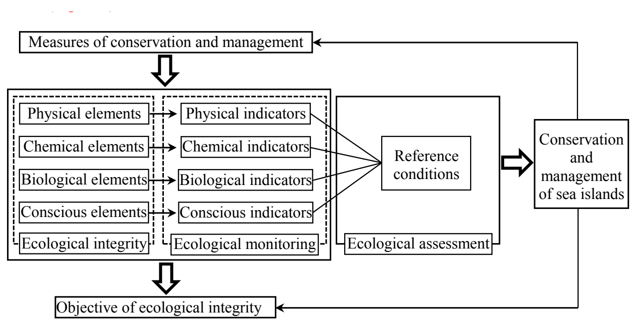

Figure 3: The application of ecological integrity in conservation and management of sea islands.

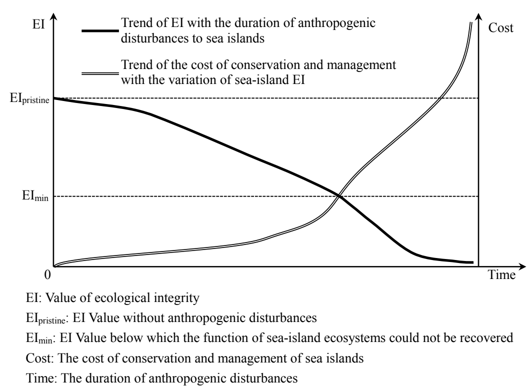

Figure 4: The frame diagram of the correlation between EI and the cost of conservation and management of sea islands.

ecological processes, and evaluating the ecological integrity of sea-islandscape ecosystems.

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