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Article

Assessment and Evolution of the Sustainable Development Ability of Human–Ocean Systems in Coastal Regions of China

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Abstract: The oceans are a crucial source of natural resources for human development, as productive terrestrial resources increasingly reach their limits of economic and ecological exploitation. With increasing human impact on oceans, it is vital to maintain a sustainable human–ocean relationship. We present an indicator system and information entropy model to assess the evolution of human–ocean systems (HOSs) according to the dissipative structure theory. Sustainable development ability (SDA) scores for HOSs are calculated based on the combination-weighting model. Finally, the Richards model is used to depict the HOSs' evolution states and periods in different coastal regions of China. The assessment indicates that total entropy is undergoing a process of negentropy; and that order degrees of HOSs are gradually improving. The results also suggest that the sustainable development levels of HOSs are continuously improving. The different coastal regions showed notable disparities of SDA and evolutionary processes, due to a differing resource base, environmental carrying capacity, and socio-economic development. Different limiting factors should determine regional policies for enhancing the SDA process; the key to sustainable development of HOS is achieving a balance between the exploitation of ocean resources for socio-economic development and conserving ecosystem services that are critical to wellbeing and livelihoods.

Keywords: sustainable development ability; human-ocean system; coastal regions of China; information entropy; Richards model

1. Introduction

Ocean ecosystems rank among the most productive ecosystems on Earth [1]. Humans—especially in coastal areas—depend on ocean systems for essential and valuable monetary (commercial activity) and non-monetary (climate regulation and food production) goods and services [2,3]. Despite their substantial productivity, oceans are extremely sensitive and vulnerable to anthropogenic disturbance. Long-term ocean- and land-based human activities increasingly represent both direct and indirect threats to the oceans. As reported by Antunes and Santos [4], the oceans face severe problems due to: (1) overfishing; (2) dumping and spills in the ocean; (3) coastal ecosystem destruction; (4) land-based contamination; and (5) pressures associated with climate change. These manifold, complex interactions and effects significantly increase levels of risk, exposure, and sensitivity of coastal communities and ocean systems and thus increase their vulnerability to human activities [5]; and even place the goal of "sustainable development"—the balanced socio-economic benefit of the marine environment—out of reach for some regions [6]. With these points in mind, sustainable development of the human–ocean systems (HOSs) has long been a focus of research and policy initiatives, despite the difficulties of understanding the relationships between multiple human activities and the status of HOSs [7].

HOSs are complex systems that comprise two relatively independent but interactional subsystems—humans and the ocean—and are understood as "all interactions and linkages between humankind and the entire ocean" [5,8]. Mono-disciplinary research can inhibit understanding of the complexity of natural systems (e.g., nonlinearity and openness) [9–11], resulting in serious misunderstanding and policy failures [12]. Researchers study these interactions and linkages from different perspectives, with the aim of improving human–ocean relationships. Clausen and Clark extended Marx's concept of the metabolic rift, developing a theoretical foundation for understanding the human–ocean relationship and the resulting oceanic crisis as it relates to the depletion of fish stocks and the expansion of aquaculture. This revealed the ecological consequences of ongoing capitalist production in relation to the ocean environment [13]. Halpern *et al.* synthesized 17 global data sets of anthropogenic drivers of ecological change for 20 marine ecosystems, and found that no area is unaffected by human influence and that a large fraction is strongly affected by multiple drivers [2]. Parravicini *et al.* developed a geospatial approach for modeling the complex relationships between multiple human pressures and coastal ecosystems status, which proved effective for modeling complex interactions among multiple pressures and for predicting potential future scenarios [7]. In addition, Land–Ocean Interactions in the Coastal Zone (LOCIZ), a core project of both the Global Environmental Change the International Geosphere-Biosphere Programme (IGBP) and the International Human Dimension Programme (IHDP) [14], have more extensive and profound meaning for sustainable solutions to the ecological and environmental problems of the coastal zone created by past, present, and future human populations [15].

The sustainable development of HOSs is bound up with harmonious relationships between human development and sustaining ecosystem services, and addresses the multiple goals of socio-economic development and environmental sustainability in a synergistic manner [16]. A number of scholars have recently argued that there are strong links between ecosystem services and sustainable development [17,18]. In HOS, the ocean ecosystem services are the linkage between ocean ecosystems and humans, that is, the specific processes that benefit people. Economic activity occurs within a network of social relationships, both of which are constrained by ecological parameters [16]. Ocean ecosystem services can be a basis for HOS sustainable development by providing a means for considering how to retain ocean resources for nature and for use by humans in a scenario growing population and, therefore, ever-increasing demand for resources. Rather than condemning societies to poverty by denying human opportunities, the challenge of sustainable development is identifying interventions in ocean ecosystems that offer human possibilities and improve livelihoods over the long term. Modifying ocean ecosystems to facilitate socio-economic development is necessary, but avoiding damaging important ocean ecosystem services is not negligible. The key challenge for HOS sustainable development is to assess trade-offs and find a balance between socio-economic development while sustaining the more important ocean ecosystem services [19]. Han and Liu studied the interactions between human societies and oceans from a geographical perspective, aiming to enrich HOS theory and marine sustainable development [20]. Halpern *et al.* provided important information regarding the sustainability of HOS development, by creating an index comprising 10 diverse public goals [21]. Using a vulnerability framework, Li established a new paradigm for the study of HOS and its sustainability [22]. Qin *et al.* introduced quantitative models for assessing human–ocean systems' sustainable development from the perspective of metabolic recycling with spatial and temporal analyses and provided important short- and long-term policies that may help enhance sustainability [8]. Comparison of those studies demonstrates that management of the sustainable human–ocean relationship calls for interdisciplinary approaches that encompass the three dimensions of sustainable development (economic development, social development and environmental sustainability).

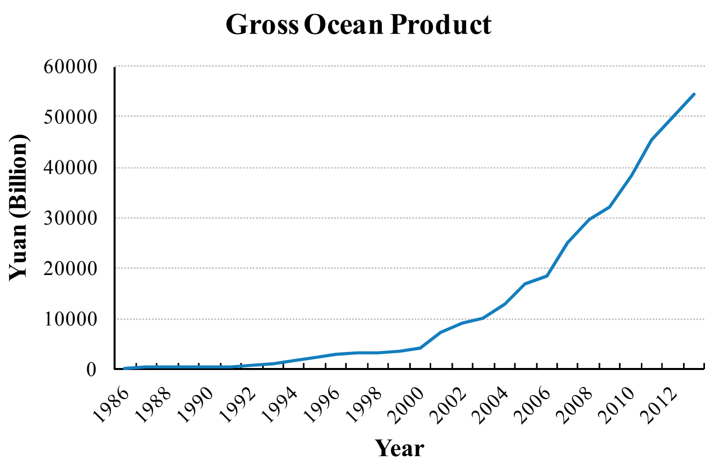

Figure 1. Growth trend of gross ocean product in China [23].

In China, the development of the marine economy is a concentrated reflection of human–ocean interaction. In the 1990s, a series of policies on ocean exploitation laid the foundation for marine economic development in China (e.g., National Marine Development Planning (1995) and China Ocean Agenda in the 21st Century (1996)). The large-scale extraction and utilization of ocean resources has driven rapid development of the marine economy (Figure 1), which has become a new highlight of the country's economic growth and an important strategic support for socio-economic development in coastal areas. Despite these achievements, the contradiction between humans and oceans has been highlighted by production factors (e.g., industrial labor, capital investment, technology, *etc.*) constantly agglomerating to oceans [24], since anthropogenic disturbance has increasingly threatened the sustainable use of the oceans. Methods for evaluating the cumulative impacts of human activities and ocean systems, and for grasping the direction, status, and stage of HOSs' evolution, are crucial for promoting integrated coastal zone management (ICZM) and achieving sustainable development of HOSs in coastal regions of China. Marine carrying capacity and marine economic sustainability assessments that synthesize socio-economic and ecological environment indicators are of great significance for the sustainable exploitation of marine resources, environmental protection, and the coordinated development of regional economies and society in coastal areas [25–28]. Along with studies on various perspectives of sustainable development such as human–ocean relationships and marine ecosystems [8,17,19,29,30], related studies have promoted sustainability management in coastal China. However, further to reviewing the existing literature, there is a need for transdisciplinary studies that combine both qualitative and quantitative approaches involved in spatial–temporal analysis; developing methods for improving the sustainable development of HOSs has become crucial, alongside the need for ICZM, and this study therefore aims to develop new methods and perspectives for studying HOSs' evolution.

2. Research Paradigm

2.1. The Driver-Pressure-State-Impact-Response Framework Analysis of Human–Ocean Systems

The Driver-Pressure-State-Impact-Response (DPSIR) framework, adopted by the European Environment Agency [31], describes a framework for analyzing and assessing the social and ecological problems by establishing cause–effect relationships between anthropogenic activities and their environmental and socio-economic consequences [32]. The causal links start with driving forces, pass through pressures to state of the environment and impacts on ecosystem functions and human welfare, eventually leading to societal responses.

In the context of the HOS (Figure 2), the *Drivers*, defined as the primary sources of external *Pressures* on coastal ecosystems, refer to the need for food, space for living, recreation, and other basic needs for social and economic development which are delivered through fisheries, recreational sites, bioremediation of waste, and so forth. Particular *Pressures* created by each of these *Drivers*, such as the exploitation of fisheries, extraction of the seabed, demands for the conservation of coastal amenity and marine biodiversity, and the discharge of contaminated waters, are exerted on the oceans though human activities. As a result, a *State* of the ocean ecosystem (e.g., the benthos or the water column) changes and produces *Impacts* on society (e.g., degraded habitats, removal of species, loss of biodiversity, *etc.*) that affect human welfare. Where threshold levels are relevant, the *Impact* of *State* change may follow accumulative effects over a period of time. Finally, alterations in the provision of ecosystem services affect human well-being which leads to human *Responses* (social, economic and political) to these changes in the HOS [33].

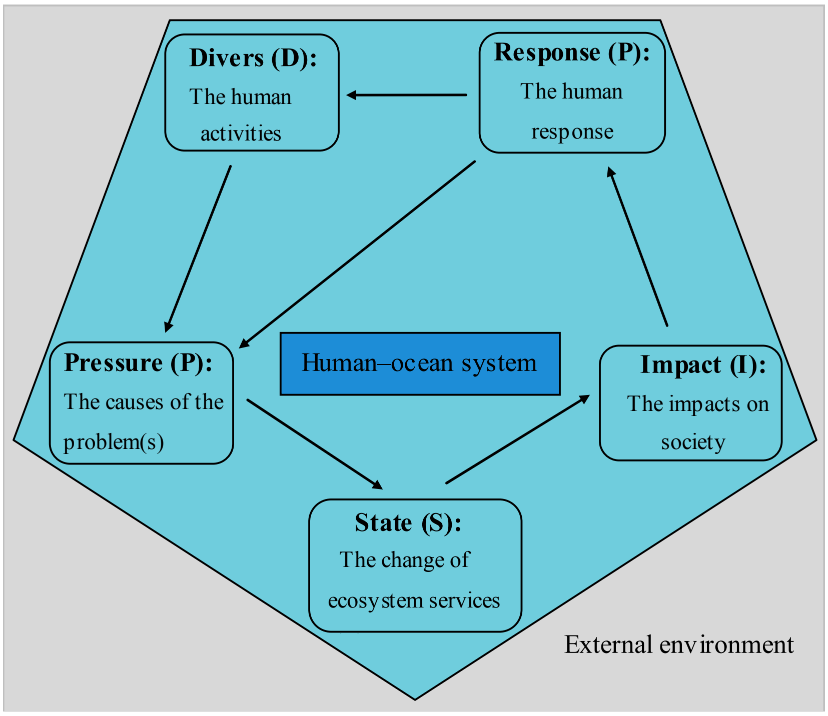

Figure 2. A visual representation of the DPSIR framework for human–ocean systems.

Since the DPSIR framework was devised in the late 1990s, international scholars have applied this framework to the evaluation of sustainable development initiatives, to better understand and overcome barriers to sustainability. Although this framework has been used extensively, it has also been subject to much criticism , based on five main shortcomings: (1) it creates a set of static indicators that serve as a basis for analysis, not taking into account the changing dynamics of the system; (2) it does not capture trends except by repeating the study of the same indicators at regular intervals; (3) DPSIR does not illustrate clear cause-effect relationships for environmental problems; (4) it suggests linear unidirectional causal chains in the context of complex environmental problems; and (5) the question of data relevance remains another concern regarding the credibility of the DPSIR framework [32,34]. Therefore, without violating the DPSIR framework, this article develops an information entropy model to assess the dynamic trend and evolution of HOSs according to dissipative structure theory.

2.2. Entropy-Based Evolution of Human–Ocean Systems

The concept of entropy has been introduced to many other disciplines, including information theory, bioscience, and environmental science, since it was first proposed by the German physicist Rudolf Clausius, and has exceeded the scope of thermodynamics and statistical physics. Among the applications of entropy, Prigogine established the inner connection between living and inanimate systems on the premise of not violating the second law of thermodynamics [35], and introduced the total entropy formula [36]. According to the dissipative structure theory, the total entropy change (d*S*) of a system can be divided into two parts with different natures: the exchange of system entropy with the external environment (entropy flow; deS); and internal entropy, produced through the evolutionary process (entropy production; diS). Hence, the total entropy formula can be represented as:

$$\mathrm{d}S = \mathrm{d}eS + \mathrm{d}iS \tag{1}$$

As open systems that are far from equilibrium during the process of exchanging matter and energy with outside environments, HOSs comply with the condition of dissipative structure, such that system evolution will follow the total entropy formula. deS is produced by exchanging material, energy, or information with its environment; the value of deS can be positive, negative, or zero. diS is generated from all types of feedback (both negative and positive) between human and ocean subsystems of HOSs. It is an inner, irreversible process of entropy increase; consequently, diS will always be positive. In addition, dS reflects the evolutionary direction and state of HOSs. In an isolated system, the second law of thermodynamics contains an "entropy increase" principle, so that dS is always greater than zero. However, to increase order within an open system, entropy reduction (negentropy) must be established in order to realize dS < 0. deS must be <0 and satisfy the condition |deS| > diS, because diS is positive. Thus, when the entropy of the system is gradually reduced, the system constantly evolves toward a more orderly state; conversely, higher entropy is associated with evolution toward a more disorderly state [37,38].

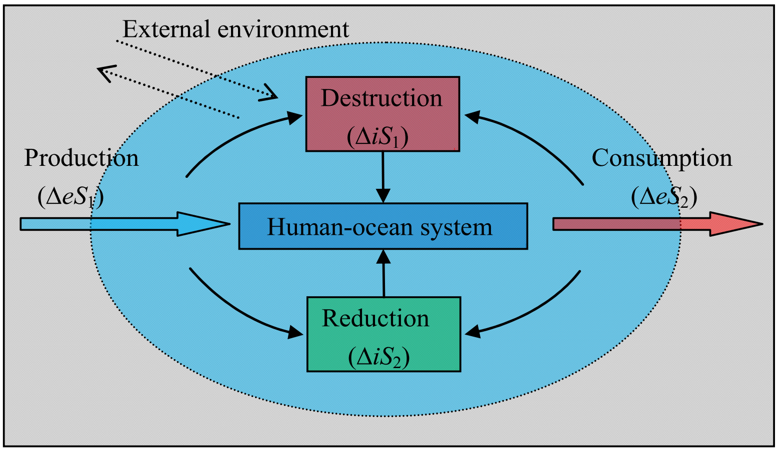

Figure 3. Basic metabolic processes in human–ocean system evolution.

Within HOSs, this article considers four basic metabolic cycle processes of production, consumption, destruction, and reduction as the system evolves (Figure 3). Production and consumption refer to the flows of material, energy, or information between systems, and also represent the productivity and capacity of HOSs, which can be treated as the deS. Destruction and reduction refer to the negative and positive feedbacks in the process of production or consumption, reflecting the degree of destruction and the protective capability of the environment, which can be regarded as diS. HOS is a thermodynamic system but is imperfect, due to the differences between thermodynamic properties of living and nonliving systems [39]. In HOSs, human activity is the most dynamic factor preventing its evolution from strictly following the second law of thermodynamics [31]. Together with the uncertainty of the system, which is exacerbated by its openness, human activity may cause diS and deS to become positive, negative, or zero [27,31,40,41].

Shannon developed information theory to a formal discipline and introduced an accurate and objective quantitative mathematical system [42,43]. Information entropy—the calculation of which closely follows Boltzmann's entropy—is a more open or generic measure with a wider range of applications for any existing data set with discrete categories [44]. In this regard, information entropy provides a solution for applying thermodynamic entropy concepts and methods to living systems, and for quantitatively describing the evolutionary state of HOSs based on the application of dissipative structure analysis.

2.3. Human–Ocean System Sustainable Development Ability Assessment and Its Evolution

The assignment of weightings significantly influences the reliability and accuracy of the environmental assessment and subsequent management decisions. Multi-criteria decision analyses (MCDA), both subjective and objective, have been widely used in social and natural sciences. Many studies have addressed the application of MCDA methods for improving decision making [45]. However, no single MCDA method can provide both subjective and objective weighting for sustainable performance criteria that SDA assessment requires [46]. Among these subjective MCDA methods, the analytic hierarchy process (AHP) [47] enjoys wide acceptance for criteria weighting through a pairwise comparison method, while EM [48,49] is more appropriate for objective weighting. Therefore, in order to systematically assess the selected scenarios against multiple management objectives, MCDA was conducted by combining two multi-criteria methods—AHP and EM—for SDA assessment.

Socio-economic and biological systems entail complex structure and causality, undergo continuous change, and contain a great deal of diversity [50]; therefore, the biological metaphor is widely used in socio-economic fields. In this context, the biological model is referred to when studying the evolution of HOSs. The Richards model, proposed in 1959, is a mathematical method for describing the process of biological evolution [51,52]. It employs a sigmoid curve to represent the three evolutionary stages: slow initial growth (biological germination), rapid growth, and steady growth (biological maturity), stabilizing at a limit state (Figure 4).

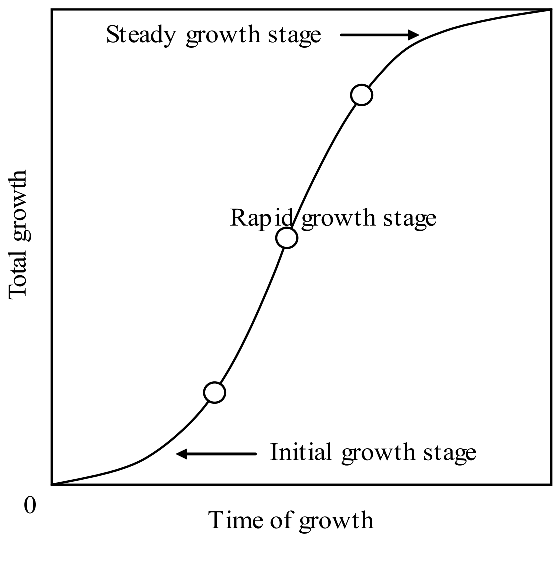

Figure 4. Sigmoid biological growth curve.

From the perspective of biological evolution, HOS evolution also undergoes the three evolutionary stages. In the germination stage, humans pay more attention to the extraction of ocean resources for social and economic development than to ecological protection. Restricted by this imbalance along with ocean development ability, degree, and scale, SDA grows at a slow rate. In the growth stage, the degree of HOS sustainability develops rapidly with improvements in the developmental ability of the ocean, increasing degree and scale of ocean utilization, and strengthening emphasis on ecological protection. The maturity stage can be regarded as advancement, but from another point of view, can be considered a bottleneck; the SDA of HOS returns to a slow growth rate, seeking transition and striving for redevelopment.

3. Material and Methods

3.1. Design of the Evaluation Indicator System

Indicators have been broadly used in the monitoring, assessment, and management of systems where simplification is required [53,54]. A few indicators cannot completely describe the state and evolution of HOSs. Instead, a framework comprising many indices representing different aspects of the processes or system is necessary to depict evolution under the influence of external perturbations and internal fluctuations [31]. Based on the principles of sustainable development, an indicator system is founded, referring to previous designs for evaluation indexes [27,31,33,34], and operate according to the scientific principles of comprehensiveness, dynamics, hierarchy, maneuverability, and perceptiveness [55,56]. This paper establishes an indicator-based system including the three dimensions of economic development, social development and environmental sustainability, which are grouped into two subsystems (socio-economic and environmental subsystem) for evaluation of sustainable development ability (SDA). Furthermore, to assess the dynamic trend and evolution of HOS, this article divides the two subsystems of specific indicators into four categories based on the four basic processes of system evolution (production, consumption, destruction, and reduction) according to the dissipative structure theory. In order to ensure relative independence between the indicators, Pearson correlation coefficients are calculated using SPSS statistical analysis software (version 19.0) (the correlation coefficient matrixes of the four sub-criteria are reported in Appendix A). The hierarchical structure of the evaluation index system is described in Table 1.

3.1.1. Socio-Economic Subsystem

(1) Supportive entropy is the material basis for system evolution and embodies the economic development level. It represents the productivity of the HOSs, which is reflected by indexes of marine products (e.g., seawater aquatic products, sea salt, marine mining) and income (e.g., per capita gross ocean product). In order to make a comprehensive assessment, indicators were selected from different marine industries according to data availability. For example, S2, S4, and S9 represent the primary, secondary, and tertiary marine industries, respectively (marine industries are classified by AQSIQ and SAC (2007)).

Table 1. Indicator system for assessing the sustainable development ability of the human–ocean system; two types of entropy (d*eS* and d*iS*) were selected as criteria, in addition to two entropy aspects for each type of sub-criterion layer (ΔeS_1, ΔeS_2, ΔiS_2, and ΔiS_1); in total, 32 representative indexes were selected; S1, Per capita gross ocean product; S2, Seawater aquatic products; S3, Sea salt production per unit area; S4, Output of offshore crude oil; S5, Output of offshore natural gas; S6, Output of marine mining industry; S7, Length of quay line per unit coastline; S8, Per capita import–export volume; S9, Per capita foreign exchange earnings from international tourism; C1, Natural population growth rate; C2, Population density; C3, Resident Consumption Level; C4, Unit GDP energy consumption; C5, Mariculture area; C6, Sea salt pan area; C7, Marine goods turnover; C8, Marine passenger turnover; C9, Number of coastal travel agencies; D1, Intensity of industrial wastewater discharged into sea; D2, Domestic sewage emissions per capita; D3, Intensity of industrial waste gas emissions; D4, Sulfur dioxide emission per unit of GDP; D5, Industrial soot (dust) emission per unit of GDP; D6, Industrial solid wastes generated per unit of GDP; D7, Direct economic loss of storm surges; R1, Output value of products made from the wastewater, waste gas, and solid wastes; R2, Investment completed in pollution treatment projects; R3, Number of environmental workers in environmental protection agency; R4, Number of coastal observation stations; R5, Per capita coastal wetland area; R6, Per capita construction of marine protect area; R7, Number of employed population of marine scientific research; negative indicators are marked by "(−)".

Criterion	Sub-Criterion	Indicator	Units	Data Sources	Subjective	Objective	Integrated
Socio-economic subsystem	Entropy flow (d*eS*): supportive entropy (ΔeS_1)	S1	yuan	[23]	0.0641	0.0371	0.0608
		S2	t	[23]	0.0154	0.0227	0.0233
		S3	t/ha	[23]	0.0081	0.0136	0.0131
		S4	$\times 10^4$ t	[23]	0.0209	0.0814	0.0514
		S5	$\times 10^4$ m^3	[23]	0.0100	0.0913	0.0377
		S6	t	[23]	0.0052	0.1312	0.0326
		S7	m	[23]	0.0399	0.0579	0.0600
		S8	US$	[23]	0.0553	0.0406	0.0591
		S9	US$	[23,57]	0.0311	0.0441	0.0462

Table 1. *Cont.*

Criterion	Sub-Criterion	Indicator	Units	Data Sources	Subjective	Objective	Integrated
Environmental subsystem	Entropy flow (deS): consumptive entropy (ΔeS_2)	C1	%	[57]	0.0061	0.0055	0.0072
		C2	person/km^2	[57]	0.0151	0.0435	0.0320
		C3	yuan	[57]	0.0355	0.0227	0.0354
		C4 (-)	Tec/×10^4 yuan	[57]	0.0255	0.0023	0.0096
		C5	ha	[23]	0.0209	0.0299	0.0312
		C6	ha	[23]	0.0104	0.0371	0.0245
		C7	×10^8 ton-km	[23]	0.0625	0.0422	0.0641
		C8	×10^8 passenger-km	[23]	0.0436	0.0341	0.0481
		C9	unit	[23]	0.0304	0.0145	0.0262
	Entropy production (diS): destructive entropy (ΔiS_2)	D1 (-)	t/×10^4	[58]	0.0752	0.0031	0.0191
		D2(-)	t/person	[58]	0.0165	0.0036	0.0096
		D3(-)	×10^4 cu.m	[58]	0.0577	0.0033	0.0173
		D4(-)	t/×10^4 yuan	[58]	0.0298	0.0025	0.0108
		D5(-)	t/×10^8 yuan	[58]	0.0231	0.0018	0.0080
		D6(-)	t/×10^8 yuan	[58]	0.0398	0.0035	0.0147
		D7(-)	×10^8 yuan	[23]	0.0080	0.0011	0.0038
	Entropy production (diS): reductive entropy (ΔiS_1)	R1	×10^4 yuan	[58]	0.0780	0.0415	0.0710
		R2	×10^8 yuan	[58]	0.0453	0.0228	0.0401
		R3	person	[58]	0.0311	0.0194	0.0306
		R4	person	[23]	0.0166	0.0171	0.0210
		R5	unit	[23]	0.0127	0.0139	0.0166
		R6	km^2	[58]	0.0077	0.0963	0.0340
		R7	km^2	[23,58]	0.0585	0.0185	0.0410

(2) Consumptive entropy embodies the consumption and social development levels of HOS in some degree, and expresses—from a different perspective—the potential pressure and disturbance within the system, caused by human activity. These pressures include population pressure, energy utilization efficiency, and anthropogenic ecological stress, which generate negative effects on the evolution and sustainable development of the system. It is worth noting that moderate consumption can generate positive effects and promote the evolution of the system. This paper selects C1 and C2 to denote population pressure, C4 for energy utilization efficiency of resources, and C5 for anthropogenic ecological stress.

3.1.2. Environmental Subsystem

(1) Destructive entropy represents the degree of environmental destruction and hazard interaction within the HOSs, which hinders sustainable development. The indexes selected for destructive entropy are wastewater, sewage, waste gas, solid wastes, sulfur dioxide, and soot (dust) emissions. D7 denotes the hazards of the ocean environment to human society. In addition, given that the HOSs are open systems, gas and water flow into and out of the systems and cannot be controlled in specific locations or regions (such as coastal zones). This is one of the reasons why HOS evolution does not strictly follow the second law of thermodynamics.

(2) Reductive entropy concerns environmental protection and regeneration capacity; it represents the governance capacity for promoting the sustainable development of HOSs. R1 was selected to denote the recyclability of waste; R2 for environmental protection input intensity; R3 and R7 for the foundations of human resource of environmental reduction; and R5 and R6 for the ecological foundation of the system.

3.2. Assessment of Human–Ocean System Evolution based on the Information Entropy Model

The information entropy model can be described as follows: in a system with uncertainty, if a random variable (X) represents the state of the system, set $X = \{x_1, x_2,\dots, x_n\}$ ($n \geq 2$); the corresponding probability for each value of X is $P = \{p_1, p_2,\dots, p_n\}$ ($0 \leq P_i \leq 1$, $i = 1,2,\dots,n$), and $\sum p_i = 1$. The information entropy can be described as:

$$S = -\sum p_i \ln(p_i) \tag{2}$$

where S is the information entropy of an uncertain system. When evaluating n indicators of HOS in m years, year-based values of S, which are calculated using annual statistics, are mainly used to calculate deS and diS. The formula can be expressed as:

$$\Delta S = -(1/\ln m)\sum_{i=1}^{n}(q_{ij}/q_j)\ln(q_{ij}/q_j) \tag{3}$$

where ΔS represents the four types of entropy: supportive entropy (ΔeS_1), consumptive entropy (ΔeS_2), destructive entropy (ΔiS_2), and reductive entropy (ΔiS_1). The parameter i ($i = 1,2,\dots,n$) represents an indicator, j ($j = 1,2,\dots,m$) represents a year. Year-based S can be expressed where x_{ij} is the value of the indicator i for year j, q_{ij} is the standardized value of x_{ij} calculated from raw data, and $q_j = \sum_{i=1}^{n} q_{ij}$.The value size of entropy can express the changes in system affordability. For the four aspects, ΔeS_1 and

ΔiS_1 are positive indicators, with larger values indicating greater coordination in the system; ΔeS_2 and ΔiS_2 are negative indicators, with larger values denoting less coordination in the system [34].

The formulae for deS, diS, and ΔS can be formed as:

$$\Delta eS = \Delta eS_2 - \Delta eS_1 \tag{4}$$

$$\Delta iS = \Delta iS_2 - \Delta iS_1 \tag{5}$$

$$\Delta S = \Delta eS + \Delta iS = (\Delta eS_2 - \Delta eS_1) + (\Delta iS_2 - \Delta iS_1) \tag{6}$$

ΔeS is generated from the discrepancy between the output and consumption levels, representing the level of harmony within the HOSs. ΔiS is generated from the difference between the degree of environmental destruction and protection capability, representing the vitality of the HOSs. ΔS is the total entropy change in each year of the study period, signifying the health status of the HOSs.

3.3. Integrated Weighting Model of Human–Ocean System Sustainable Development Ability Assessment

Vector $w_{1i} = (w_{11}, w_{12}, \ldots, w_{1n})$ contains weightings determined by AHP. For the AHP weight of each indicator, given that all types of entropy are indispensable, the four types of entropy are equally important. Specific indicator weights are determined by means of expert consultation, according to their importance for the sustainable development of the HOSs (Table 1) (the pairwise comparison matrixes of the four sub-criteria are reported in Appendix B). Vector $w_{2i} = (w_{21}, w_{22}, \ldots, w_{2n})$ contains those determined by EM. Vector $W_i = (W_1, W_2, \ldots, W_n)$ is the combined weight where $i = 1,2,\ldots,n$. In order to ensure W_i is as close as possible to w_{1i} and w_{2i}, according to the principle of minimum relative information entropy, the optimization function is expressed as:

$$\min F = \sum_{i=1}^{n} W_i(\ln W_i - \ln w_{1i}) + \sum_{i=1}^{n} W_i(\ln W_i - \ln w_{2i}) \tag{7}$$

where $\sum_{i=1}^{n} W_i = 1, W_i > 0,\ i = (1,2,\cdots,n)$. Using the Lagrange multiplier method [59], the optimal solution is given by:

$$W_i = \sqrt{w_{1i} w_{2i}} \Big/ \sum_{i=1}^{n} \sqrt{w_{1i} w_{2i}}\ , i = (1,2,\cdots,n) \tag{8}$$

Thus, the SDA scores of HOSs can be calculated as the weighted sum of different indicators X_{ij} in different samples:

$$Z_i = \sum_{i=1}^{n} X_{ij} W_{ij}\ , (i = 1,2,\ldots,m, j = 1,2,\ldots,n) \tag{9}$$

where the range of Z_{ij} is [0–1], X_{ij} is the standardized value of indicator j for sample i, and W_{ij} is the weighting of the indicator.

3.4. Analysis of Human–Ocean System Evolution based on the Richards Model

The Richards model can be expressed in differential form:

$$dX/dt = (rX/\lambda) \cdot \left[1 - (X/K)^{\lambda}\right] \tag{10}$$

If initial conditions are given by $X(t_0) = X_0$, then the general form of the Richards equation can be expressed as:

$$X(t) = K/(1+Be^{-r(t-t_0)})^{1/\lambda} \quad (11)$$

where K is the development index threshold of the system, representing the maximum capacity of the system, and $K > 0$; r is the growth rate of the system development index, and $r > 0$; λ is the comprehensive influence index; $B = \lambda C$; and finally, C is the integration constant. In the Richards model, the shape of the curve changes with λ (Figure 5). Due to the dissimilarity between resource endowment and socio-economic development, HOSs have different regional evolutionary characteristics. This paper maintains that the development index of the system $K = 1$, because the SDA values were between 0 and 1 following data standardization; the growth rate r was the average growth rate of the SDA values, which was calculated using $r = (SDA_{2012}/SDA_{1996})^{[1/(n-1)]} - 1$ and λ was an estimated parameter. SPSS (version 19.0) was used to fit the nonlinear Richards equation.

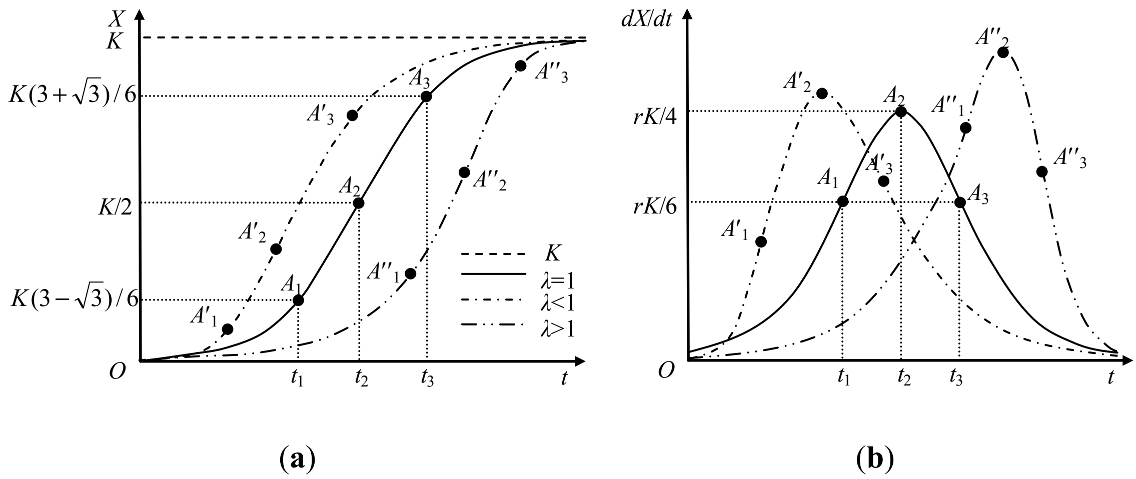

Figure 5. Human–ocean system development index and speed based on the Richards model. (**a**) development index; (**b**) development speed.

The characteristics of the Richards curve as a function λ value are as follows:

(1) When $\lambda = 1$, the Richards curve is a logistic curve. The development index curve is centrosymmetrical, whose center is point A_2. The development speed curve is symmetrical, showing that the speed of development is the same in the earlier and later periods. However, the condition of $\lambda = 1$ is theoretical and is not observed in practice.

(2) When $\lambda < 1$, the speed of system development peaks earlier in the evolutionary process. Development speed is faster in the earlier period than in the later period, whereas the later period is of longer duration. The entire evolutionary process shows an initially quick then slow trend.

(3) When $\lambda > 1$, initial development is slow and becomes faster toward the end, peaking relatively late in the evolutionary process, contrary to that observed when $\lambda < 1$.

The turning points A_2, A'_2, and A''_2, where the second derivative of the Richards equation is zero (Figure 5a), divide the curve into two segments that respectively represent the earlier and later periods in the HOS evolutionary process. The turning points in Figure 5b denote the changes of development speed [60].

HOS evolution is divided into three stages of germination, growth, and maturity according to the turning points where the second and third derivatives of the Richards equation are zero (Table 2) [51,61].

Table 2. Division of changes in human–ocean system evolution based on the Richards model.

Point	t	X	dX/dt	Evolutionary Stage
	$(0, t_1)$	Slow growth	Uptrend	Germination
A_1 (A'_1, A''_1)	t_1	$K(1+\lambda R_1)^{-1/\lambda}$	$rKR_1/(1+\lambda R_1)^{1+1/\lambda}$ (turning point)	
	(t_1, t_2)	Rapid growth	Uptrend	Growth
A_2 (A'_2, A''_2)	t_2	$K(1+\lambda)^{-1/\lambda}$	$rK/(1+\lambda)^{1+1/\lambda}$ (maximum)	
	(t_2, t_3)	Rapid growth	Downtrend	
A_3 (A'_3, A''_3)	t_3	$K(1+\lambda R_2)^{-1/\lambda}$	$rKR_2/(1+\lambda R_2)^{1+1/\lambda}$ (turning point)	Maturity
	$(t_3, +\infty)$	Slow growth	Downtrend	

3.5. Data Sources and Processing

3.5.1. Data Sources

Marine data collection at province level began in 1996 in China; hence, the chosen study period is 1996–2012. Data were extracted from the China Marine Statistical Yearbook (1997–2013) [23], China Statistical Yearbook (1997–2013) [57], and China Statistical Yearbook of Environment (1997–2013) [58].

3.5.2. Data Processing

The reliability of the assessment was improved by using the Min–Max method to normalize each indicator (range 0–1) in order to eliminate the effects of magnitude (units of measurement) and attributes (positive or negative). The following data processing methods were used: (a) information entropy model for HOS evolution assessment used the four types of entropy for vector quantization, avoiding the need to distinguish between positive and negative indicators for standardization; (b) the SDA assessment model did not use vector quantization for different types of indicators, such that the positive and negative indicators must be distinguished for data processing. To assess the n indicators in m samples, the standardizing equations are as follows:

For a positive indicator:

$$X_{ij} = \left[x_{ij} - \min_j(x_{ij})\right] / \left[\max_j(x_{ij}) - \min_j(x_{ij})\right] \tag{12}$$

For a negative indicator:

$$X_{ij} = \left[\max_j(x_{ij}) - x_{ij}\right] / \left[\max_j(x_{ij}) - \min_j(x_{ij})\right] \tag{13}$$

3.6. Study Area

The coastal region of China (Figure 6), which refers to all regions with coastlines (both continental and island coastlines), is located in the east and south of the Chinese mainland, comprising provinces, autonomous regions, and municipalities that are directly administered by the central government [23], from north to south: Liaoning, Hebei, Tianjin, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Guangxi, and Hainan. Taiwan Province, Hong Kong, and Macao special administrative regions are excluded from this study, as data are unavailable. The total length of coastline is about 32,000 km (18,000 km continental and 14,000 km of island coastline). In 2012, the total population was 584.63 million, accounting for 43.18% of total national population; GDP was 31,589.42 million yuan, accounting for 60.87% of total national GDP.

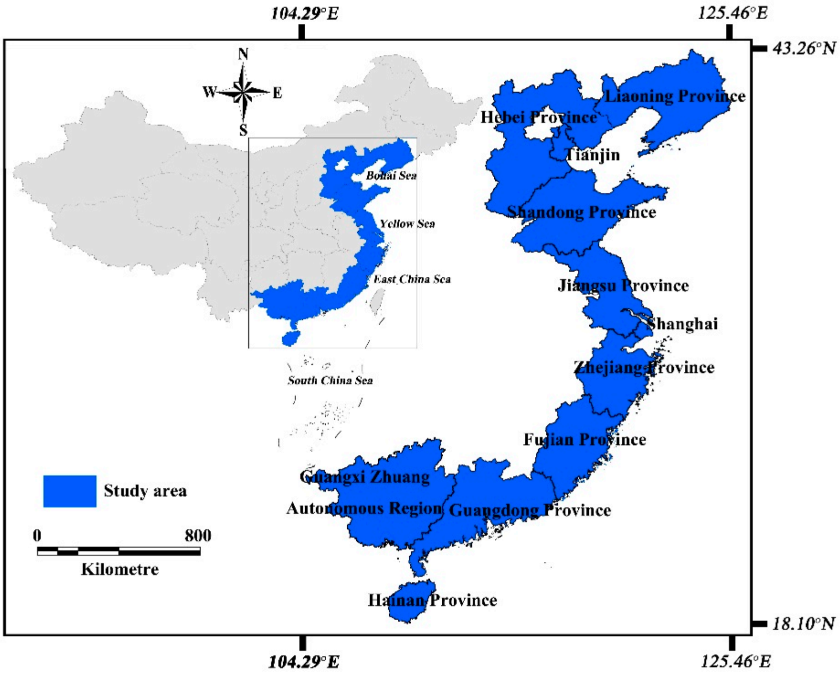

Figure 6. Coastal regions of China.

The rapid growth of the Chinese economy has been increasingly concentrated in the coastal regions [62]. These regions have become some of the most developed areas of the economy, with the highest degree of international exposure and the highest population densities. The contribution of the marine economy was 15.84% in 2012 [23]. However, population growth and the continual exploitation of ocean resources are having increasingly negative effects on coastal systems.

4. Results

4.1. Information Entropy-Based Analysis

4.1.1. Four Types of Entropy

After each indicator was standardized using the Min–Max normalization method, Equation (3) was used in the information entropy model and the four types of entropy were calculated for the HOSs in different regions. The results from 1996–2012 and mean values are listed in Figure 7.

The four types of entropy showed different trends during the study period, as shown in Figure 7. There were significant upward trends for ΔeS_1 and ΔiS_1 in most provinces, except ΔeS_1 of Shanghai and Guangdong, and ΔiS_1 of Tianjin and Jiangsu, which rose initially and then dropped. This suggests that ocean development and environmental protection were improving in most coastal provinces. ΔeS_2 in most provinces increased in the first stage and then decreased, except in Guangxi and Hainan where there was an uptrend. The entropy value of ΔiS_2 fluctuated initially and then decreased rapidly. It can be inferred from these trends that the ecological pressures of human activity on the HOSs are displaying predictable decline; pollution emission levels are falling in the coastal regions of China.

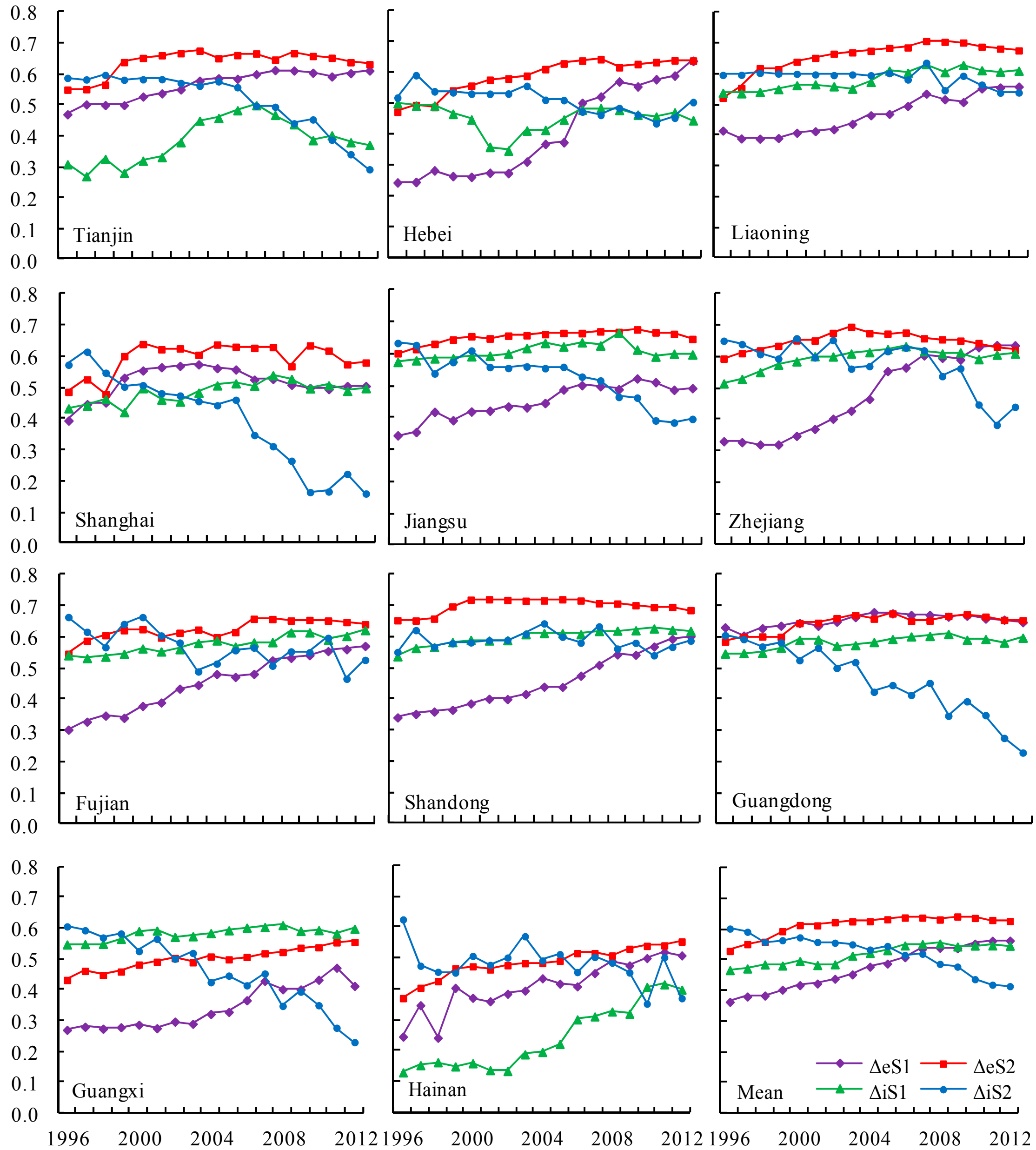

Figure 7. Four types of entropy value of human–ocean systems in coastal regions of China, 1996–2012.

4.1.2. Entropy Flow, Entropy Production, and Total Entropy Change

Entropy changes can reflect the evolution and state of HOSs. For further analysis, regional deS, diS, and dS were calculated using Equations (4)–(6) from 1996–2012, as shown in Figure 8.

Figure 8 shows that most of the provinces have positive ΔeS. Overall, although the processes influencing ΔeS vary, a clear trend of initial increase was followed by a decrease. The magnitude of the decrease was greater than that of the increase. Some exceptions are the ΔeS of Zhejiang, which was negative in 2011, and ΔeS of Guangdong, which fluctuated between positive and negative values. Shanghai and Guangdong experienced fluctuations, resulting in an indistinct trend. The main reason for the trend of ΔeS in most of the provinces is that ΔeS_1 and ΔeS_2 showed concurrent increases, whereas ΔeS_2 initially increased then decreased. Improved energy efficiency plays an important role in the ΔeS_2 trend, which can be explained from the downtrend of the unit GDP energy consumption index. Moreover, mariculture and marine saltpan areas in most provinces follow the same overall trend (initial increase followed by a decrease). The findings confirm that ecological pressures on the HOSs have recently become less severe.

With the exception of some individual provinces (e.g., Hebei), ΔiS showed an overall declining trend in most provinces. The ΔiS values fluctuated from positive to negative and those of Shanghai and Guangdong were lower than in other provinces. The ΔiS_2 trend was similar to that of ΔiS, which suggests that a decrease in ΔiS_2 significantly affects ΔiS. For example, the decrease in ΔiS_2 in Shanghai and Guangdong is much larger than that in other provinces, whose ΔiS values are lower. These phenomena are caused by reduced discharge of pollutants such as wastewater and gas.

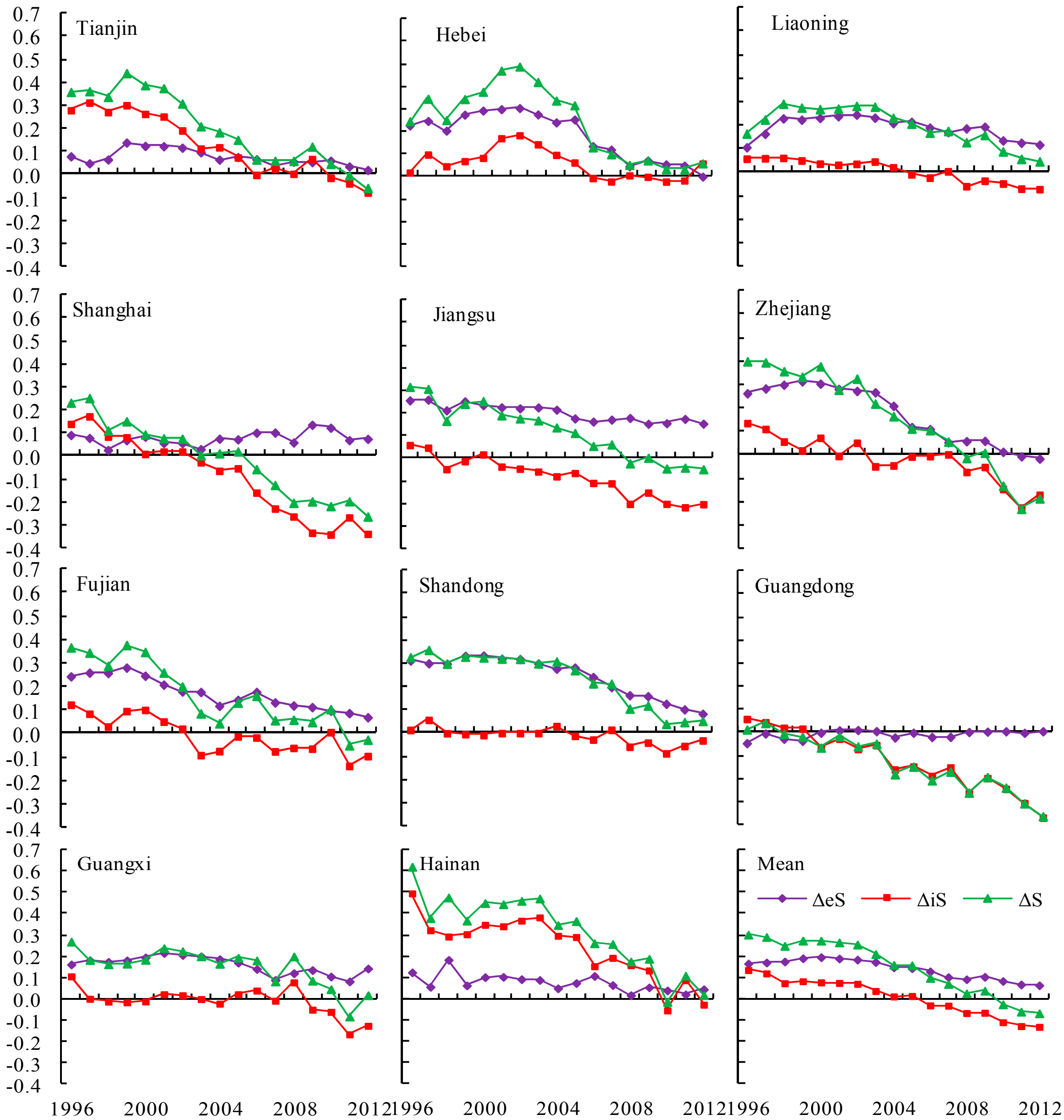

Figure 8. Entropy flow, entropy production, and total entropy change of the human–ocean systems in coastal regions of China, 1996–2012.

The coastal provinces show declining ΔS values, typically with slow initial decline becoming more rapid, but with differences between the trends observed in each region. ΔS values for Hebei, Tianjin, and Liaoning provinces initially increased and then decreased. ΔS values of Guangdong and Shanghai were lower than those of other provinces, which was attributed to high energy-efficiency, low pollution emission, and powerful environmental protection. The ΔS of most provinces reached the negative phase in 2012, except for Hebei, Liaoning, Shandong, Guangxi, and Hainan (which approached the negative phase). This indicates that the total entropy of each of these HOSs is decelerating, and that the degrees of order within the system are gradually improving.

4.2. Sustainable Development Ability of the Human–Ocean System

The SDA scores represent the level and stage of HOSs sustainable development, where higher values denote greater sustainability. To calculate the SDA scores, the weight of each indicator was decided by the integrated weighting model of AHP-EM.

Generally, the SDA scores for the HOSs of various coastal regions improved during the study period. The sustainable development capacities of the HOSs were enhanced. This supports the results presented in Section 4.1.2, which detail the trend of declining entropy among coastal province HOSs: increasing order and enhanced SDA. Moreover, notable differences are seen between the different regions (Figure 9). Due to the high levels of ocean development and environmental protection capacity, SDA values for Shanghai, Guangdong, and Shandong increased during the research period, from 0.1823, 0.2433, and 0.2076, respectively, in 1996, to 0.5150, 0.4592, and 0.4480 in 2012. Hebei, Guangxi, and Hainan were restricted by limited ocean resources and development capacity; their SDA scores were low and development was slow, with SDA scores increasing from 0.0874, 0.0931, and 0.1287, respectively in 1996, to 0.1529, 0.2337, and 0.2141 in 2012. Although the five remaining provinces showed strong ocean development potential, their corresponding capacity for environmental protection could not match the intensity of development, which resulted in intermediate SDA scores.

Among the coastal regions of China, Tianjin, Shanghai, and Guangdong all show comparatively high potential for developing their ocean economies. Per capita gross ocean products of Tianjin and Shanghai grew to 27,875.31 and 24,979.94 *yuan* by 2012. However, the SDA of Tianjin is much lower than that of Shanghai, due to differing environmental protection ability together with weak ocean resource base; furthermore, the investment in pollution treatment projects and the number of workers employed in the environmental protection agency are lower than the averages for coastal China. As to Shandong, the ocean economy development ability is inferior to that of Tianjin, whereas environmental protection ability is much higher. Shandong invests five times more than Tianjin in pollution treatment projects, and by 2012 had the largest number of staff employed in marine scientific research in coastal China. Therefore, the SDA of Shandong is higher than that of Tianjin. The SDA of Hebei and Guangxi are restricted by both ocean resources base and ocean development capacity. Hainan Province has advantages in terms of resources and environmental conditions, but its potential to develop ocean resources is lower and the strength of its ocean scientific research is obviously weaker than other provinces. In 2012, Hainan only had 192 persons employed in marine scientific research, which is far lower than the average number of 2024 in coastal China.

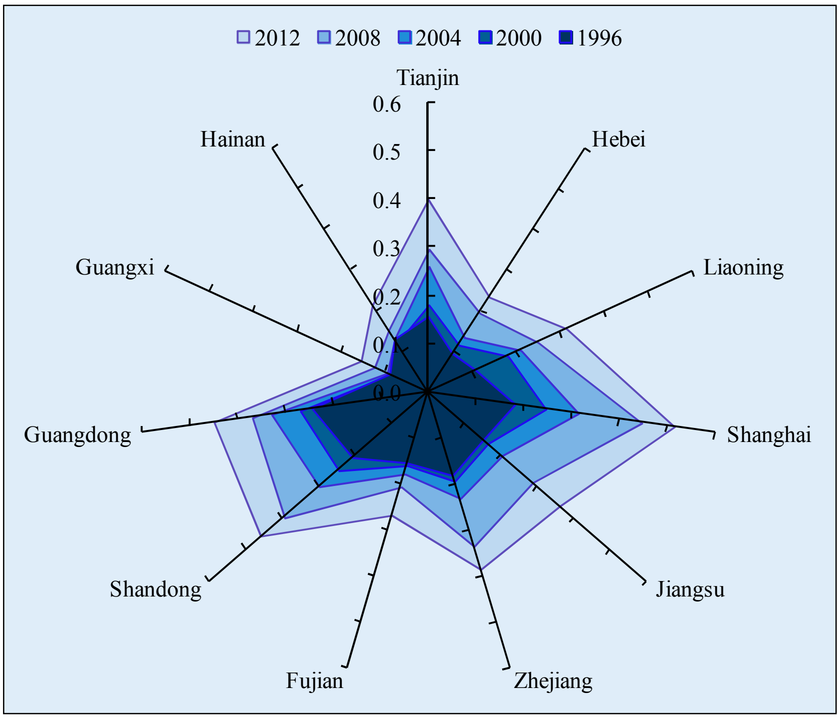

Figure 9. Sustainable development ability of human–ocean systems in different regions from 1996–2012.

4.3. Analysis of Human–Ocean System Evolution based on the Richards Model

Based on the hypothesis that HOS evolution follows the laws of biological evolution, this paper used the Richards model to depict HOSs evolution states and periods for the different regions using the calculated SDA scores. The Richards equation includes three parameters. The results are listed in Table 3.

Table 3. The Richards equation and evolution of HOSs in coastal regions of China.

Region	r	λ	R-Squared	Evolution Curve	Development Speed
Tianjin	0.0611	0.5448	0.9504	Steep at first, smooth later	Quick at first, slow later
Hebei	0.0592	0.8612	0.9754	Steep at first, smooth later	Quick at first, slow later
Liaoning	0.0694	0.6312	0.9238	Steep at first, smooth later	Quick at first, slow later
Shanghai	0.0671	0.2571	0.9564	Steeper at first, smoother later	Quicker at first, slower later
Jiangsu	0.0560	0.7790	0.9040	Steep at first, smooth later	Quick at first, slow later
Zhejiang	0.0487	0.5962	0.8826	Steep at first, smooth later	Quick at first, slow later
Fujian	0.0356	0.9808	0.8502	Steep at first, smooth later	Quick at first, slow later
Shandong	0.0509	0.3190	0.9693	Steeper at first, smoother later	Quicker at first, slower later
Guangdong	0.0389	0.4273	0.8957	Steeper at first, smoother later	Quicker at first, slower later
Guangxi	0.0355	1.0647	0.8211	Smooth at first, steep later	Slow at first, quick later
Hainan	0.0323	1.0933	0.7572	Smooth at first, steep later	Slow at first, quick later

As shown in Table 3, the R-squared values of the nonlinear fitting of the Richards equation are adequate for determining the statistical significance of the estimated λ and HOSs evolution trends in various regions. The numerical size of λ varies between provinces. Table 3 shows that most of the λ values are less than 1, except for Guangxi and Hainan. Shanghai had the smallest λ value, while Hainan had the largest. There were three numerical ranges of λ in the 11 regions: those of Shanghai, Shandong, and Guangdong were less than 0.5. Their HOSs' evolution curves were the steepest initially and the smoothest later. The sustainable development level of the HOSs in these provinces enhanced very rapidly in the early stages, and then very slowly in the mature stages. Values of λ in Guangxi and Hainan were larger than 1. Their HOSs evolution curves were the smoothest initially and the steepest later. The sustainable development level of HOSs in these provinces were enhanced smoothly in the early stages, and quickly in the mature stages. The evolutionary processes were quite different. λ in the other provinces ranged between 0.5 and 1.

The HOS evolution stage for each province can be determined using the turning points during the period 1996–2012 (Table 2). The results are summarized in Table 4.

Table 4. Turning points and evolutionary stage of HOSs in coastal regions of China.

Region	R_1	R_2	At_{1996}	At_1	At_2	At_3	At_{2012}	Evolutionary Period
Tianjin	3.2358	0.3090	0.1549	0.1548	0.4501	0.7515	0.3999	Growth
Hebei	3.5820	0.2792	0.0931	0.1951	0.4861	0.7787	0.2337	Germination to growth
Liaoning	3.3310	0.3002	0.1075	0.1663	0.4606	0.7596	0.3147	Germination to growth
Shanghai	2.9139	0.3432	0.1823	0.1136	0.4107	0.7197	0.5150	Growth to maturity
Jiangsu	3.4927	0.2863	0.1512	0.1851	0.4774	0.7722	0.3622	Germination to growth
Zhejiang	3.2925	0.3037	0.1802	0.1617	0.4564	0.7564	0.3857	Growth
Fujian	3.7114	0.2694	0.1532	0.2091	0.4981	0.7873	0.2683	Growth
Shandong	2.9839	0.3351	0.2076	0.1229	0.4198	0.7273	0.4592	Growth to maturity
Guangdong	3.1053	0.3220	0.2433	0.1386	0.4349	0.7395	0.4480	Growth to maturity
Guangxi	3.8017	0.2630	0.0874	0.2186	0.5061	0.7930	0.1529	Germination
Hainan	3.8324	0.2609	0.1287	0.2218	0.5088	0.7949	0.2141	Germination

There are five important points listed in Table 4: At_{1996} and At_{2012} are SDA values at the beginning and end of the evolutionary period for different regions; At_1 is the turning point from the germination stage to growth; At_2 is peak development speed; and At_3 is the turning point from the growth stage to maturity. The HOS evolutionary period for each province can be determined by comparing the numerical size at the beginning and end with the two turning points. For example, the initial point At_{1996} of Tianjin is 0.1549, which is greater than the turning point At_1 = 0.1548, but smaller than the turning point At_3 = 0.7515. This suggests that, at the beginning of the study period, Tianjin was in its growth stage. The end point At_{2012} is 0.3999, which is much less than At_3 = 0.7515. Thus, the Tianjin HOS underwent a period of growth during the entire evolutionary period. According to these principles, four HOS evolutionary periods were recognized in the 11 provinces.

Comparing Tables 3 and 4, it was found that the smaller the size of λ, the closer was the HOS to the mature evolutionary stage; conversely, larger λ is associated with closer proximity to the germination stage. For example, λ values for Shanghai, Shandong, and Guangdong were less than 0.5; their HOSs evolution reached maturity in 2012, especially for Shanghai, which has the smallest λ value of 0.2571. The λ values for Guangxi and Hainan are greater than 1; their HOSs evolution is still in the germination stage, with a slow growth rate.

5. Discussion and Conclusions

Anthropogenic effects on ocean systems are now widely recognized but are often difficult to quantify [63]. Coupled with the complex and unpredictable characteristics of these interactions, an accurate method of assessment can be a useful decision-making tool for sustainable development management [64]. With reference to ecological studies, an information entropy model was developed in this study to assess the evolutionary development of HOSs. We found that the ΔS of most coastal provinces in China had reached (or approached) the negative phase in 2012. This indicates a deceleration of the total entropy of the HOSs, gradually increasing order of the systems, and evolution in a healthy and orderly direction. Furthermore, the SDA scores of various coastal provinces showed constant improvement throughout the study period, indicating increasing capacity for sustainable development. Regardless of the differences in study area, scale, and perspective, these findings are broadly similar to those of Yu *et al.* [65], Li *et al.* [19], Li [66], Di *et al.* [26], and Qin *et al.* [8], who reported increasing SDA of HOSs in coastal regions of China.

The broad concept of sustainable development [67] is characterized by three dimensions: economic development, social development, and environmental sustainability [16]. Different resource and environmental carrying capacities and socio-economic development levels will have appreciable impact on SDA in different regions. Shanghai, Guangdong, and Shandong have the most promising scores, as a result of their relatively high levels of socio-economic development. By contrast, Hebei, Guangxi, and Hainan had low SDA scores and developed slowly, which was attributed to limited resources and lower socio-economic development.

Finally, the Richards model was used to depict the state and period of HOSs evolution in different regions. The magnitudes of λ varied between the provinces. Most λ values were less than 1, with the exception of Guangxi and Hainan. Shanghai had the lowest λ and Hainan had the highest. λ was the key indicator of differing regional SDA values and evolutionary processes, and showed positive correlation with system entropy and negative correlation with SDA score. For example, the ΔS values of Guangdong and Shanghai were lower than those of other provinces, as were their λ values; however, their SDA scores were higher.

Regional policies for enhancing the SDA of HOSs are influenced by different limiting factors. Non-integrated ocean protection or development is inappropriate for the sustainable development of HOSs. For example, Hainan Province has the largest protected marine area in coastal China but its ocean development ability is below average, which is reflected by the comparatively low gross ocean product. Therefore, the SDA of the HOS in Hainan is comparatively weak, and it is in the germination stage of HOS evolution. In this regard, policies for sustainable development of the HOSs in provinces like Hainan must pay more attention to developing the oceans on the premise of ensuring the ecological quality of the marine environment. However, for provinces like Tianjin, policies for sustainable development of the HOSs should focus on environmental protection.

Sustainable development depends on maintaining ecosystem services. The key to sustainable development of HOS is achieving a balance between the exploitation of ocean resources for socio-economic development while conserving ecosystem services that are critical to societal wellbeing and livelihoods. For example, ecosystem-based approaches (EBAs) that consider socio-economic development in the context of ecosystem dynamics could effectively improve the sustainable development of ocean ecosystems [68]. Holistic, integrated responses have the potential to effectively address issues related to ecosystem services and human well-being simultaneously [16]. For policy planning, a better understanding of the resource and environment exploration levels, energy efficiency, pollution levels, and environmental protection capacity are needed in order to enhance the SDA of HOSs in different regions. ICZM can promote the overall sustainability of China's coastal areas [69]. Nevertheless, sustainable development is the responsibility of all parts of society, *i.e.*, governments, public interest groups, consumers, and the private sector [70]. Unlike other coastal states, where public participation or community-based engagement was key to the success of ICZM, stakeholder involvement in ICZM programs in China has usually been quite weak and received insufficient attention, due to the current top-down management approaches [63]. Principles such as stakeholder consultation should inform sustainable development strategies for the HOSs of coastal regions of China.

The present study has several limitations: Sustainable development itself is a multi-dimensional concept and demands consideration of trade-offs among environmental, social, and economic impacts [58]. Restrictions on data availability make it difficult to choose indicators that cover all aspects of the HOS. Moreover, sustainability requires a long-term perspective, whereas the currently available data are short-term and incomplete. The number of studies on complex systems has increased recently. We believe that new tools and techniques for analyzing complexity will be created in the near future, and intend to focus on such improvements in our future research.

Acknowledgments

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Author Contributions

Caizhi Sun, Kunling Zhang, Wei Zou, Bin Li, and Xionghe Qin produced the paper and all co-authors contributed to the data collection and calculations.

Conflicts of Interest

The authors declare no conflict of interest.

Appendix A

Correlation coefficients were calculated in SPSS (version 19.0). The results are listed in Tables A1–A4. A coefficient > 0.9 between two indicators implies that the indicators overlap and should be merged.

Table A1. Coefficient calculation matrix of supportive entropy indicators.

	S1	S2	S3	S4	S5	S6	S7	S8	S9
S1	1.0000	−0.1512	−0.0422	0.4263	0.2184	0.0771	0.7776	0.8446	0.8356
S2		1.0000	0.4544	−0.0401	0.1113	0.2026	−0.4262	−0.2065	−0.1966
S3			1.0000	0.0948	−0.1938	0.1307	−0.2282	−0.3266	−0.3448
S4				1.0000	0.7070	−0.1146	0.2691	0.3018	0.2825
S5					1.0000	−0.1026	0.1297	0.3800	0.3472
S6						1.0000	−0.0991	0.0676	0.0314
S7							1.0000	0.8020	0.8114
S8								1.0000	0.8990
S9									1.0000

Table A2. Coefficient calculation matrix of consumptive entropy indicators.

	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	1.0000	−0.6077	−0.3763	−0.1458	−0.1489	−0.1016	−0.4840	−0.0455	−0.2104
C2		1.0000	0.6513	−0.1748	−0.2861	−0.1496	0.7623	−0.0201	0.0870
C3			1.0000	−0.5269	0.0176	−0.1723	0.8250	0.1861	0.4934
C4				1.0000	0.0632	0.3398	−0.3135	−0.1174	−0.3040
C5					1.0000	0.5192	−0.0567	0.5686	0.5520
C6						1.0000	−0.1097	0.1510	0.4362
C7							1.0000	0.0963	0.2602
C8								1.0000	0.4124
C9									1.0000

Table A3. Coefficient calculation matrix of destructive entropy indicators.

	D1	D2	D3	D4	D5	D6	D7
D1	1.0000	−0.0383	0.0198	−0.0246	0.0746	0.2330	0.1096
D2		1.0000	−0.3556	−0.4490	−0.4549	−0.4317	−0.0243
D3			1.0000	0.6076	0.5512	0.8396	−0.2352
D4				1.0000	0.8933	0.6003	−0.0920
D5					1.0000	0.6083	−0.1161
D6						1.0000	−0.1396
D7							1.0000

Table A4. Coefficient calculation matrix of reductive entropy indicators.

	R1	R2	R3	R4	R5	R6	R7
R1	1.0000	0.5654	0.5446	0.2377	−0.1835	−0.0710	0.2470
R2		1.0000	0.6560	0.4196	−0.1400	−0.0795	0.4340
R3			1.0000	0.3073	−0.2943	−0.1339	0.1977
R4			0.3073	1.0000	0.0993	−0.0656	0.3542
R5					1.0000	0.2758	−0.0615
R6						1.0000	−0.1432
R7							1.0000

Appendix B

Public consultation was an important aspect of the AHP weighting for each indicator in this study. Experts from different fields, including ecology, economics, economic geography, and ocean governance, were consulted extensively on the weighting of each indicator shown in the following tables (Tables B1–B4).

Table B1. Pairwise comparison matrix of supportive entropy indicators.

	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**Weight**
S1	1	4	5	3	6	7	2	2	3	0.0641
S2		1	2	1/2	3	4	1/3	1/4	1/3	0.0154
S3			1	1/3	2	3	1/4	1/6	1/5	0.0081
S4				1	3	5	1/3	1/4	1/2	0.0209
S5					1	2	1/4	1/6	1/3	0.0100
S6						1	1/6	1/7	1/6	0.0052
S7							1	1/2	2	0.0399
S8								1	2	0.0553
S9									1	0.0311

For a better understanding of the table, consider the following example. The value in the first row and fourth column is 3, which means that S1 is three times as important as S4. The consistency ratio of the pairwise comparison matrix is found to be 0.0362, and as the value is under 0.10, we conclude that the comparison matrix is consistent.

Table B2. Pairwise comparison matrix of consumptive entropy indicators.

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**Weight**
C1	1	1/3	1/5	1/4	1/4	1/3	1/6	1/6	1/5	0.0061
C2		1	1/2	1/2	1/3	/2	1/3	1/2	1/3	0.0151
C3			1	2	3	3	1/3	1/2	2	0.0355
C4				1	2	3	1/2	1/2	1/2	0.0255
C5					1	3	1/3	1/2	1/2	0.0209
C6						1	1/5	1/4	1/3	0.0104
C7							1	2	3	0.0625
C8								1	2	0.0436
C9									1	0.0304

Table B3. Pairwise comparison matrix of destructive entropy indicators.

	D1	**D2**	**D3**	**D4**	**D5**	**D6**	**D7**	**Weight**
D1	1	4	2	3	3	2	6	0.0752
D2		1	1/3	1/3	1/2	1/2	1/3	0.0165
D3			1	3	2	3	5	0.0577
D4				1	2	1/2	4	0.0298
D5					1	1/3	4	0.0231
D6						1	5	0.0398
D7							1	0.0080

The consistency ratio of the pairwise comparison matrix is 0.0432 (Table B2).
The consistency ratio of the pairwise comparison matrix is 0.0483 (Table B3).

Table B4. Pairwise comparison matrix of reductive entropy indicators.

	R1	R2	R3	R4	R5	R6	R7	Weight
R1	1	2	3	4	5	7	2	0.0780
R2		1	2	3	5	5	1/2	0.0453
R3			1	3	4	4	1/3	0.0311
R4				1	2	3	1/5	0.0166
R5					1	3	1/3	0.0127
R6						1	1/5	0.0077
R7							1	0.0585

The consistency ratio of the pairwise comparison matrix is 0.0476 (Table B4).

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