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Donor-side evaluation of coastal and marine ecosystem services

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ABSTRACT

There is an increasing need for coastal and marine ecosystems conservation. However, information to guide management decisions for coastal and marine ecosystems is still lacking. Considering the present advantages and limitations of existing ecosystem services valuation (ESV) accounting methods, this paper proposes a detailed donor-side accounting approach, based on emergy method, which could be used as the basis for better policies-making on coastal and marine conservation. In particular, this includes a classification of different ecosystems, a system for ecosystem services (ES) classification, ES formation mechanism, as well as accounting techniques. The ES classification system includes direct, indirect and existence services. Accounting techniques presented here can overcome common limitations in existing accounting methods: (1) double counting; (2) evaluation from the receiver perspective; (3) the inappropriate use and replacement of unit emergy value (UEV). The present method is applied to the evaluation of coastal and marine ecosystems in the Pearl River Delta (PRD), China. Results show that (1) the total coastal ESV decreased from 2000 to 2009 in the PRD area, among which water purification contributes most to the decrease, followed by soil building, climate regulation and microclimate regulation; (2) the coastal ecosystems have the largest potential to regulate climate whether at micro or macro scale; (3) the marine ESV decreased with the ratio of 42.37%, and biomass increase and carbon sequestration account for the decrease; (4) intertidal marshes has the largest ESV per unit area, followed by mangrove, coral reefs and rocky marine shores, while the marine ecosystem has the smallest ESV per unit area. As proved by the case study, this work can provide a basis for an accounting method for coastal and marine ESV assessment, which could serve to improve both the management decision making processes and policy indications through accurately valuing coastal and marine ES, leading to additional investment in conservation of these ecosystems.

1. Introduction

Marine and coastal ecosystems are highly valuable due to their richness in productivity and diversity (Wilkinson, 2008; Finlayson et al., 2018). The huge list of Ecosystem Services (ES) provided includes habitats for flora and fauna, floods and storms mitigation, sediment retention, erosion control and carbon storage (Brown et al., 2006; Barbier et al., 2011). In parallel, they have a beneficial impact on the people living in coastal areas and small islands, which account for one third of the global human population (Barbier et al., 2008). The overexploitation of these areas results in habitat destruction, climate change, pollution and invasive species growth (MEA, 2005; Barbier, 2017; Newton et al., 2018). A further expansion of urbanization and economic development has significantly influenced coastal sustainability (Dobson et al., 2006; Halpern et al., 2008; Bateman et al., 2011; Murray et al., 2014; Yang et al., 2018). As remarked by Costanza et al. (2014) and Ellis et al.

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(2015) it is unlikely that these pressures will decrease in the short future.

Protection plans and actions are still lacking, even if the public's perception of marine ecosystems conservation is improving. Due to difficulties and costs of working at sea, marine ecosystems conservation, exploitation and restoration are commonly undervalued in decision-making (Camacho-Valdez et al., 2014; Vassallo et al., 2018). Consequently, marine protection measures are less developed than terrestrial ones (UNEP-WCMC and IUCN, 2016), even if many nations (such as China, United Stated, Canada and so on) and international NGOs that are cooperating to develop implemented policies in this field. This is why many marine ecosystems are under pressure (Watson and Hewson, 2018; Xia et al., 2017; Sun et al., 2018b; Lirman et al., 2019).

It would be highly desirable to expand the protection of coastal and marine waters up to 10% by 2020, as fixed under the Convention on Biological Diversity (CBD) (Coates, 2016; Roberts et al., 2018). Therefore, it is critical to develop a clear and transparent process for ES assessment. However, the uniqueness and complexity of coastal and marine ecosystems bring challenges to coastal and marine ESV assessment. In detail, it is critical to evaluate marine and coastal ES, with adequate consideration of their uniqueness and features, to provide conservation and management suggestions and to preserve the benefits that ES give to humans (Sandhu et al., 2018).

Three main methods were implemented to assess ESV (Langan et al., 2018). The first one is economic method. Twenty years ago, Costanza et al. (1997) applied an economic method to assign a value to the world's ES. Other researchers used this method to develop several applications and policies (Braat and Groot, 2012). Costanza et al. (2017) revisited this method, concluding that its main advantage is that it is easier to understand values of ecosystem services when they are expressed in monetary units. However, other researchers criticized some weaknesses of this choice. In fact, using a monetary approach, the quantification of ES becomes rooted on individual well-being assessment or perception (Costanza et al., 2017). Instead, human wellbeing should be more than an aggregate of individuals' welfare, depending also on the welfare of each community or society (Costanza et al., 2017; Campbell, 2018). Moreover, individuals might not adequately perceive all the things that contribute to their wellbeing (Fioramonti, 2014). The second dilemma related to limited applications of this approach. For example, Costanza et al. (2017) recently proposed some mistaken identities concerning ES and ESV. In fact, economic value does not necessarily equate to the market value, meaning that expressing values in monetary units does not equal to market or exchanging values.

Conservation and natural resource management can be approached evaluating ES with InVEST model (Ouyang et al., 2016). For example, coastal ES, their spatial patterns, as well as their dynamics were assessed applying this approach (Tallis and Polasky, 2009; Yang et al., 2017). However, it lacks unified metrics and simulation of the dynamic ecological processes (Tallis and Polasky, 2009; Bhagabati et al., 2014; Langan et al., 2018).

This is why an alternative option, based on a donor-side approach, was implemented to evaluate the ecosystem support provided to humans (Franzese et al., 2017). This method is called emergy analysis method. Solar emergy is solar energy required directly and indirectly to make a service or product (unit: solar emjoules (sej)) (Odum, 1996). Emergy is a donor-type value, which is determined by the production process and not by human's preferences or willingness to pay (Odum, 1996). One significant concept of this method is Unit Emergy Values (UEVs) (emergy intensities), which is the amount of emergy required to produce a given amount of mass or energy of a product, measured in units of sej/g, sej/J and sej/$ (Brown and Ulgiati, 2004). Emergy accounting, based on a donor-side evaluation of biophysical stocks and flows, to assess the environmental costs of any production, quantifies the cumulative available energy expenditure in making and, eventually, operating any service or good (Odum, 1996). Emergy method, rooted on thermodynamic principles, can be used to detail the flows of resources (both materials and energy) within any system. This method has been already applied in ES assessment and to measure the technological transformation of natural resources (Campbell and Brown, 2012; Campbell, 2012; Turcato et al., 2015; Yang et al., 2018).

The application of emergy method still lacks a framework in its application to coastal and marine ESV. In fact, economic approaches are still prevailing (Li et al., 2013; Canu et al., 2015; Pendleton et al., 2016; Sun et al., 2016, 2018a). This study aims to fill this research gap. In particular, this research aims at providing a "supply-side" evaluation of coastal and marine ESV, capturing the dynamic ecological processes and applying a unified metrics to ESV accounting. The method is applied to a case study: the region of Pearl River Delta (China). Finally, some policy recommendations for marine and coastal ecosystems conservation, management and restoration are also suggested.

2. Methods

2.1. Description of study area

The Pearl River Delta (PRD hereafter), China, is located in the downstream alluvial plain of the Pearl River in China. Covering an area of 3000 km^2, its extension ranges from 21°30′ N to 23°42′ N, and from 112°26′ E to 114°24' E (Liu et al., 2017). Nine cities, located in Guangdong Province, belong to this area: Guangzhou; Shenzhen; Zhuhai; Foshan; Huizhou; Dongguan; Zhongshan; Jiangmen; Zhaoqing.

The data about PRD region coastal ecosystems, referred to years 2000 and 2009, are presented in Table 1 (Administration, 2015). Han et al. (2006) defined a coastal ecosystem as "the area including coastal lowlands, tidelands, and shallow waters (less than 6 m in depth during low tide) that is usually submerged by an immobile or flowing water body under sea-land alternation processes". Besides terrestrial areas, coastal ecosystems include water bodies with depth lower 2 m, corresponding to a distance from shore of 1 km. Also, due to the unavailability of DEM data on China's coastal areas, the coastal areas that the distance from shore is fixed at 3 km. This limit is selected as the coastal ecosystems in case study (Fig. 1).

Chester and Jickells (2012) defined a marine ecosystem as the area where waters have a depth higher than 6 m and having a high salt content, i.e. with an average salinity of 35 parts per thousand of water. Territorial waters is an area of coastal waters extending at most 12 nautical miles (around 22.2 km) from the baseline of a coastal state. Inland sea may be located between coastal ecosystems and territorial sea. Due to the unavailability of China territorial sea baseline, the areas ranging from the exterior line of coastal ecosystems and extending to 12 nautical miles are selected as marine ecosystem for the case study. The geographical distribution of coastal and marine ecosystems applied to this case study is shown in Fig. 1. Mangrove ecosystem is selected to detail the specific calculation process in an accompanying Methods article in the journal of MethodsX and all the UEVs used in this study also attached in the article for reference.

2.2. Coastal and marine ESV accounting method

The framework of coastal and marine ESV accounting method (Fig. 2) include: ecosystem classification, ES classification, ES

Table 1
The coastal ecosystems cover changes in the PRD region from 2000 to 2009.

Coastal ecosystems types	2000	2009	Change (2000–2009)	
	Area (ha)	Area (ha)	Area (ha)	%
C1-Shallow marine waters	103680.1623	127054.13	23373.97	23%
C2-Marine subtidal aquatic beds	1889	112.74	−1776.26	−94%
C3-Coral Reefs	1221	230.71	−990.29	−81%
C4-Rocky marine shores	360.19	812.6	452.41	126%
C5-Intertidal sand/shingle/pebble beaches	5600.64	2193.22	−3407.42	−61%
C6-Intertidal mud/sand flats	16543.47	7282.08	−9261.39	−56%
C7-Intertidal marshes	2495.56	129.08	−2366.48	−95%
C8-Mangroves	3720.35	3427.58	−292.77	−8%
C9-Permanent estuarine waters	243928.12	167266.49	−76661.63	−31%
C10-Estuarine systems of deltas	0	7312.62	7312.62	–
C11-Coastal brackish/saline lagoons	2882.13	3932.32	1050.19	36%
Total	382320.63	319753.57	−62567.06	

Note. Data derive from the two China wetland resources surveys, ended in 2000 and 2010 and referred to years 2000 and 2009.

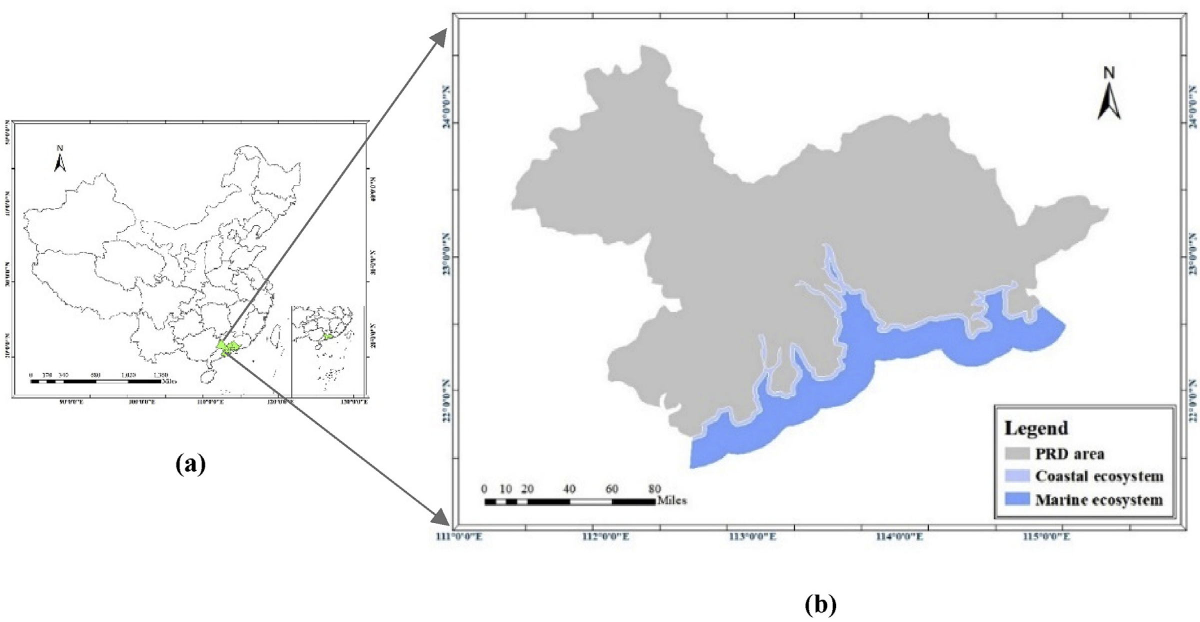

Fig. 1. The location of areas for the present case study, referred to the Pearl River Delta (PRD) (b) and its location in China (a).

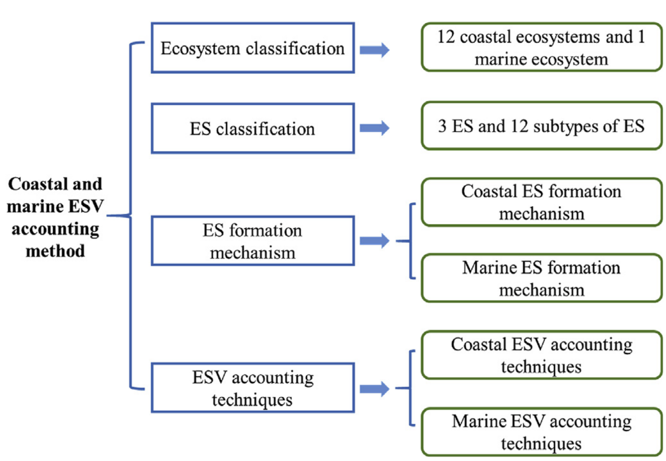

Fig. 2. The framework of coastal and marine ESV accounting method in this study (see section 2.2.1, 2.2.2 and 2.2.3 for more details).

formation mechanism and ESV accounting techniques, which will be detailed as follows.

2.2.1. Coastal and marine ecosystems and their services classification

Investigated ecosystems include: marine shallow waters (C1); subtidal marine aquatic beds (C2); coral reefs (C3); rocky marine shores (C4); intertidal sand/shingle/pebble beach (C5); intertidal mud/sand flats (C6); intertidal marshes (C7); mangroves (C8); permanent estuarine waters (C9); estuarine systems of deltas (C10); coastal brackish/saline lagoons (C11); coastal freshwater lagoons (C12). The characters of these coastal and marine ecosystems are shown by Table 2(Jiang et al., 2015).

ES are categorized into three types: direct, indirect and existing services. The first one quantifies the changes in flows and storages within the studied ecosystem. It mainly includes biomass increase, carbon sequestration, soil building and sedimentation. The second one accounts for co-products and by-products of the ecological processes in producing the direct services. There, water, air and soil purification, microclimate regulation and electricity generation are accounted. The third quantify the local share of global ES, as well as

Table 2
List of coastal and marine ecosystems used in this study and their main characteristics.

No.	Types	Characteristics
C1	Shallow marine waters	<6 m deep at low tide; vegetation cover <30%; include sea bays and straits
C2	Marine subtidal aquatic beds	Existing vegetation under water; vegetation cover ≥30%; include kelp and sea grass beds, as well as tropical marine meadows
C3	Coral Reefs	Abundant in coral reefs; including coral island and coral beach
C4	Rocky marine shores	Rock bottom >75%; Vegetation cover <30%; include rocky inlands and cliffs
C5	Intertidal sand/shingle/pebble beaches	Vegetation cover <30%; sand and/or shingle bottom
C6	Intertidal mud/sand flats	Vegetation cover <30%; mud or sand bottom
C7	Intertidal marshes	Vegetation cover ≥30%; saltwater marshes
C8	Mangroves	Abundant in Mangroves; intertidal marshes
C9	Permanent estuarine waters	Semi-enclosed body of water connected to the sea as far as the tidal limit or the salt intrusion limit and receiving freshwater runoff
C10	Estuarine systems of deltas	Formed from deposition of sediment carried by a river; vegetation coverage <30%
C11	Coastal brackish/saline lagoons	Coastal brackish or saline lagoons
C12	Coastal freshwater lagoons	Coastal freshwater lagoons
M	Marine ecosystem	Water depth >6 m; high salt content (avg. salinity ≥35‰)

Source: Jiang et al. (2015).

ecosystem cultural and educational values. Climate regulation, biodiversity conservation, cultural and education values are accounted as main existing services. These categories and components are assigned to the different ecosystem types according to the scheme reported in Table 3.

2.2.2. Diagram representation of coastal and marine ES

Coastal and marine ES dynamics are represented using emergy systems diagrams by Fig. 3 and Fig. 4. These representations are developed according to the symbolic language used by the system ecologist H. T. Odum and followers (e.g.: Odum, 1996; Odum and Odum, 2000; Brown, 2004).

Fig. 3 shows the energy system diagram of coastal ecosystem services. From left to right, renewable sources including sunlight, rain and so on drive photosynthesis. In this process, carbon can either be returned to the atmosphere through respiration or stored within the biomass of plant, such as mangroves or seagrass in intertidal zone. After the death of plants, carbon moves from aboveground to the soil as one source of soil organic matter. Similarly, from left to right as well as from outside to inside, due to river flux and tidal variations, oxygen, salinity and nutrient availability are constantly fluctuating, resulting in mangrove soils, found between terrestrial and marine environments, formed and deposited by fine particles rich in nutrients, organic matter.

Yet, wastewaters discharged into river and tide would cause pollution in coastal environments, while coastal ecosystems have potential to remove water pollutants. Except for water purification capacity, coastal ecosystems, especially mangroves, have the ability to purify air and soil pollutants. Meanwhile, driven by wind and tidal energy, electricity can be generated in coastal ecosystems. However, if without the protection of coastal plants, coasts would be easily eroded.

On the right side of the emergy analysis diagram, the uniqueness of coastal ecosystems location makes it significant habitats for species, resulting in their high value in biodiversity. In addition, integrating with water bodies and vegetation, coastal ecosystems contribute a lot to climate regulation at both micro and macro scales. The higher hierarchy flows in coastal regions are the information carried which is educational and cultural value in the perspective of ecosystem service.

Fig. 4 shows that on the left of marine system diagram, sunlight drives the photosynthesis, during which carbon is sequestrated from air to deep ocean through biological process, thus increasing marine biomass. Except for this biological carbon pump, at the bottom of the diagram, there are another two carbon pumps: physical and solubility pump. The former refers to vertical deep mixing occurs when warm ocean surface waters at low latitudes is transported to high latitudes and then cooled, resulting in the

Table 3
Classification of coastal and marine ecosystem services according to ecosystem types.

Ecosystem types	Ecosystem services classification											
	Direct services				Indirect services					Existing services		
	BI	CS	SB	SS	WP	AP	SP	MR	EG	CR	BC	C&E
Coastal ecosystems												
C1-Shallow marine waters	✓	✓			✓	✓		✓	✓	✓	✓	✓
C2-Marine subtidal aquatic beds	✓	✓			✓	✓		✓		✓	✓	✓
C3-Coral Reefs	✓	✓			✓	✓		✓		✓	✓	✓
C4-Rocky marine shores	✓	✓						✓		✓	✓	✓
C5-Intertidal sand/shingle/pebble beaches	✓	✓						✓		✓	✓	✓
C6-Intertidal mud/sand flats	✓	✓						✓		✓	✓	✓
C7-Intertidal marshes	✓	✓			✓	✓		✓		✓	✓	✓
C8-Mangroves	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
C9-Permanent estuarine waters	✓	✓			✓	✓		✓		✓	✓	✓
C10-Estuarine systems of deltas	✓	✓			✓	✓		✓		✓	✓	✓
C11-Coastal brackish/saline lagoons	✓	✓			✓	✓		✓		✓	✓	✓
C12-Coastal freshwater lagoons	✓	✓			✓	✓		✓		✓	✓	✓
Marine ecosystem	✓	✓			✓	✓		✓		✓	✓	✓

Note: BI: Biomass increase; CS: Carbon sequestration; SB: Soil building; SS: Soil sedimentation; WP: Water purification; AP: Air purification; SP: Soil purification; MR: Microclimate regulation; EG: Electricity generation; CR: Climate regulation; BC: Biodiversity conservation; C&E: Cultural and education value. The same below. "√" means the ecosystems have the corresponding services.

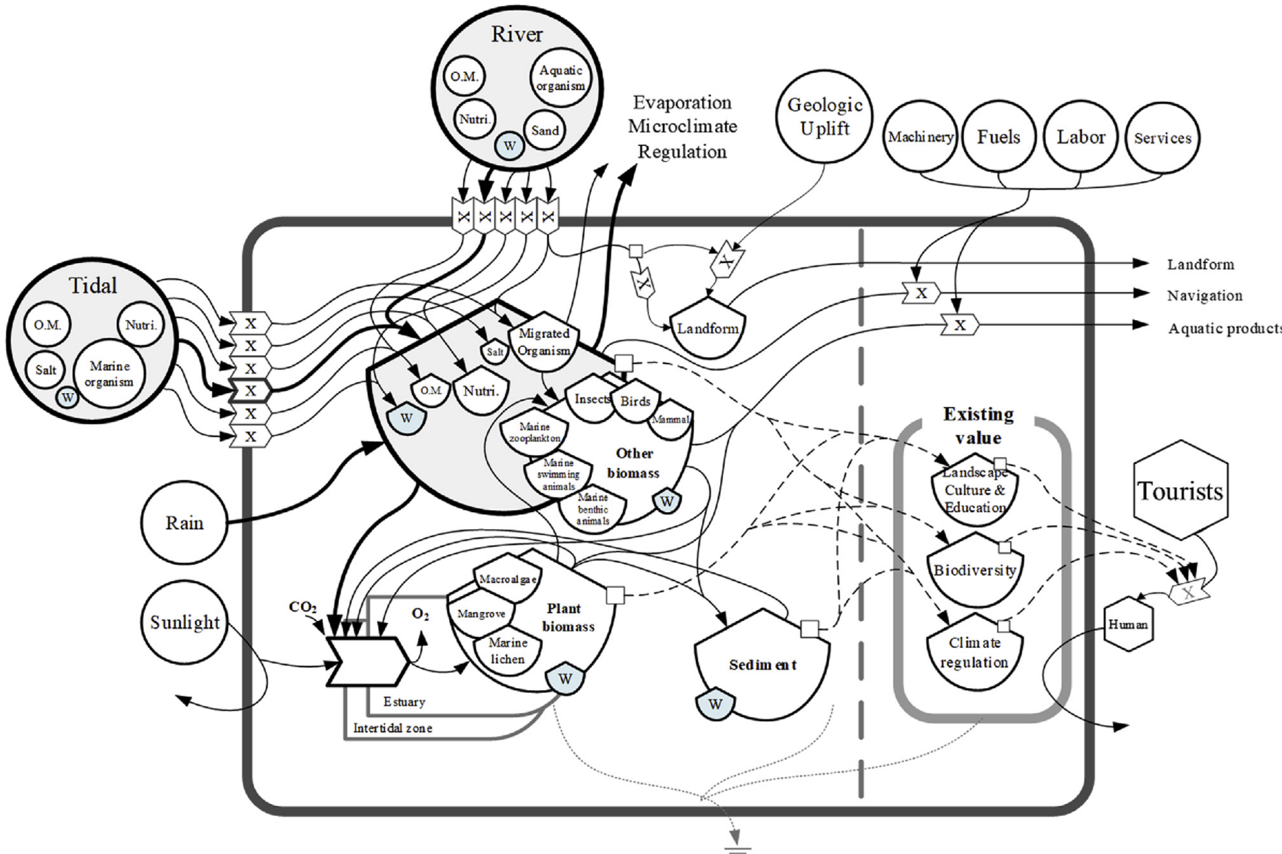

Fig. 3. Emergy analysis diagram of coastal ecosystem services (O.M.: organic matter; Nutri: nutrients; W: waste).

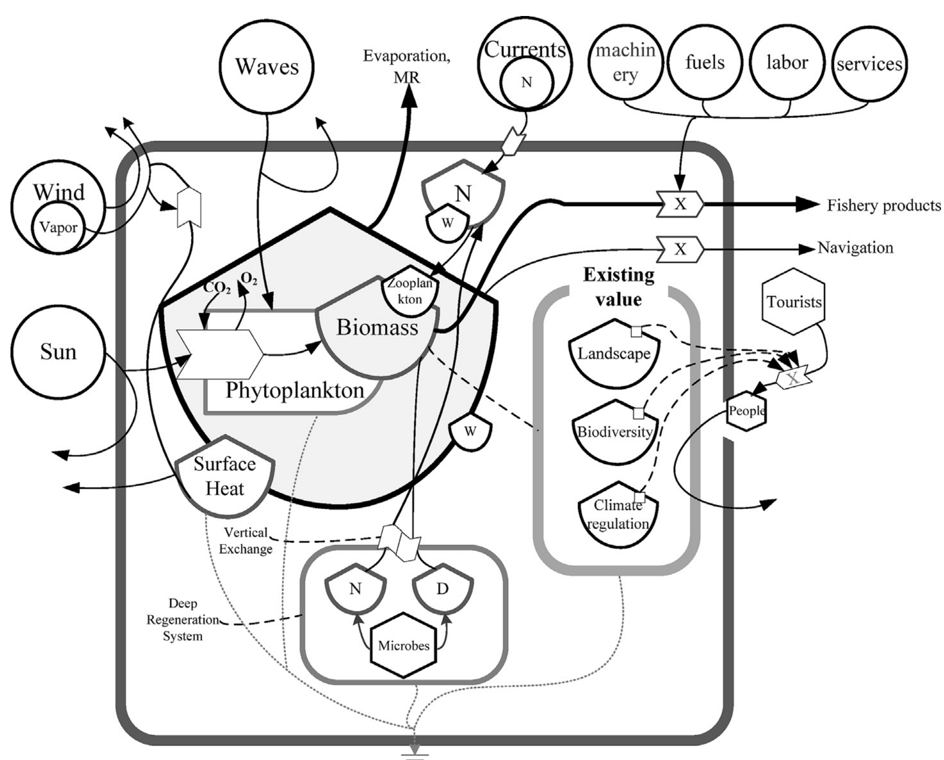

Fig. 4. Systems diagram of marine ecosystem services (N, nutrients; W, waste; D, detritus; MR, microclimate regulation).

water heavy enough to sink (Thompson et al., 2017). Solubility carbon pump is the process by which carbon is carried from air into ocean through gas transfer.

On the middle and right side of the diagram, due to the large amount of water volume, marine ecosystem has strong capacity of self-purification, climate regulation at local and global scales, as well as an extensive phylogenetic biodiversity than terrestrial ecosystems (Jenkins and Van Houtan, 2016). Similar to coastal ecosystem, marine region offers educational and cultural value as a form of information service on the right.

2.2.3. Coastal and marine ESV accounting techniques

The coastal and marine ESV accounting techniques are detailed in the accompanying Methods article in the journal of MethodsX.

3. Results

3.1. Coastal and marine ESV in the study area

According to the Coastal and marine ESV in the study area are evaluated here. As shown in Fig. 5 and Table 3, coastal ecosystems area decreased by 16% during 2000–2009.

In particular, coastal ESV are 2.93E+21 sej (year 2000) and 2.76E+21 sej (year 2009), with a 6% year decrease rate. With the exception of biomass increase and carbon sequestration (63.09% growth rate), all the other ecosystem services decreased. Among them, water purification contributes most to this trend (−53.22%), followed by soil building (−45.27%), climate regulation (−16.37%) and microclimate regulation (−15.74%).

For marine ecosystem, the total ESV in study area decreased around 42.37%, from 2000 to 2009, with the ESV decreasing from 2.16E+21 sej to 1.76E+21 sej, as shown by Fig. 5. Biomass increase and carbon sequestration contributes all the decrease because the climate regulation service of marine keeps stable during 2000–2009.

Considering the components of ES separately, for coastal ecosystems, indirect services account most for the total ESV, with the percentage of 72.13% (year 2000) and 64.31% (year 2009) respectively. In 2000, the existing and direct services contribute 14.83% and 13.04% respectively to the total coastal ESV, while their proportion are 13.17% and 22.52% in 2009, indicating the increase in direct services.

To be more specific, coastal ecosystems in the PRD area have the largest potential of microclimate regulation with the ratio of 71.13% in 2000 and 63.67% in 2009, followed by climate regulation, accounting for 14.83% in 2000 and 13.17% in 2009, and biomass increase and carbon sequestration (12.95% in 2000 and 22.44% in 2009). These indicate coastal ecosystems have strong microclimate

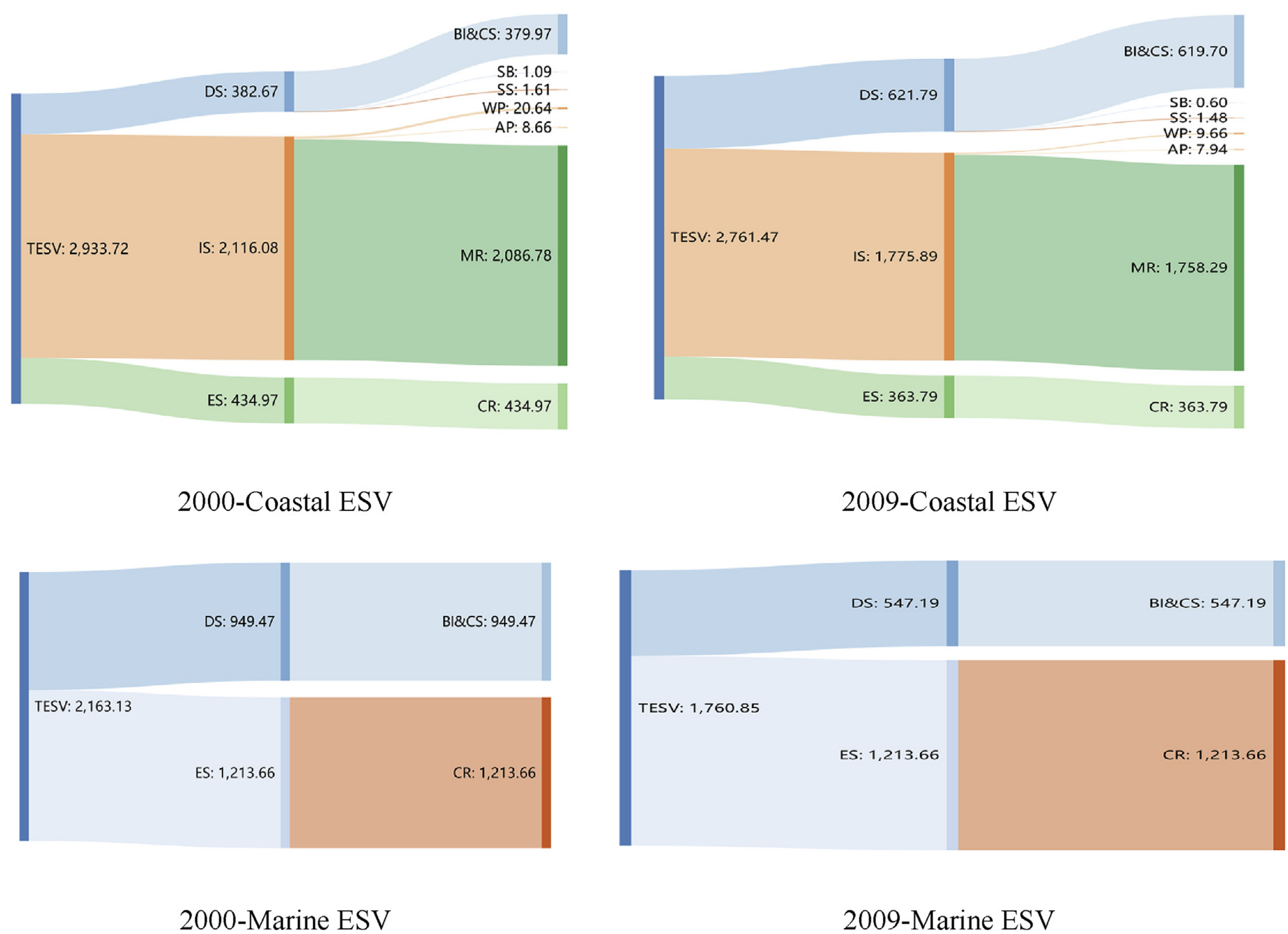

Fig. 5. The changes in coastal and marine ESV from 2000 to 2009 (unit: E+18sej) (TESV, Total ecosystem services valuation; DS, Direct services; IS, Indirect services; ES, Existing services; BI & CS: Biomass increase and Carbon sequestration; SB: Soil building; SS: Soil sedimentation; WP: Water purification; AP: Air purification; MR: Microclimate regulation; CR: Climate regulation.).

and climate regulation services in local and regional scale.

For marine ecosystem, climate regulation service contributes 56.11% and 68.92% to the total ESV in 2000 and 2009 respectively, indicating the large potential to regulate climate, which is consistent with the coastal ecosystems in the PRD region.

3.2. Coastal and marine ESV per unit area

Coastal and marine ESV per unit area, during 2000–2009, are presented in Fig. 6. In particular, intertidal marshes had the highest ESV per square meter (1.44E+12 sej/m^2 in 2000, 1.40E+12 sej/m^2 in 2009), followed by mangrove (1.27E+12 sej/m^2 and 1.18E+12 sej/m^2 in 2000 and 2009 respectively), rocky marine shores (1.16E+12 sej/m^2 in 2000 and 6.08E+11 sej/m^2 in 2009) and coral reefs (1.01E+12 sej/m^2 in 2000 and 8.53E+11 sej/m^2 in 2009). The absence of estuarine systems for deltas in 2009 leads to year 2009 ESV per unit area equal to zero. The marine ecosystem has the smallest ESV per unit area compared to coastal ecosystems.

4. Discussion

4.1. General discussion

From the calculation results of case study, both coastal and marine ESV decreased, from 2.93E+21 sej/yr to 2.76E+21 sej/yr and from 2.16E+21 sej/yr to 1.76E+21 sej/yr during study period. In the case of coastal ecosystems, water purification contributed most to the decrease followed by soil building. According to the accounting techniques of water purification, i.e. equation (S9) and (S10), M_{ij}, $DALY_i$, PDF_i are constant parameters, and τ_H is also the same in year 2000 and 2009, because it is replaced with the emergy per capital in Guangdong province in 2012 (Lin et al., 2018). Based on accounting detail presented in the accompanying Methods article in the journal of MethodsX, the changes in ecosystem areas triggered the changes in E_{msp}. Consequently, it was the decrease in coastal areas that caused the degradation of coastal ecosystem services. This is a result of the high exploitation of coastal regions by humans (Murray et al., 2014). As a consequence, it would be relevant to increase the protection of coastal area to preserve its ES. In particular, planners should try to plan a wider conversion of these regions into protected natural reserves. Biomass increase accounts for the decrease in marine ESV, mainly caused by the decline in rainfall, from 2000 to 2009, while the other services are stable during study period.

Because of the scarcity of data on biodiversity (i.e. species density, uniqueness, trophic levels and so on), the related ESV is presently underestimated. Therefore, appropriate monitoring technologies should be applied to collect sufficient information for such a purpose. After many years, as already claimed by Manley et al. (2006), it would be still highly desirable to define a national framework for species inventory and monitoring.

The application of the method to estimate the educational and cultural values through emergy accounting, as defined by Abel (2010, 2013), would be difficult in the case of ESV, since a framework is still missing for such a purpose.

4.2. Specific topics

4.2.1. Water supply

Water desalination is important for several countries to address water shortages. According to Zheng et al. (2014), China's total seawater desalination ability grew from 10,000 m^3/d to roughly 660,000 m^3/d from 2000 to 2011. However, a higher target is set for 2020, reaching 2.5–3 million m^3/d. Desalination needs both natural contributions (such as seawater) and artificial inputs (such as fuels, filter membrane, chemicals and so on) (Buenfil, 2001). Because ESV assessment is based on emergy method in this study, thus only seawater's contribution is needed to be included in the ESV evaluation. Yet, according to Odum (1996), there is no specific emergy of seawater, because it is saltwater and the chemical potential is zero. Therefore, water supply service of coastal and marine ecosystems is excluded in this study. While for freshwater ecosystems,

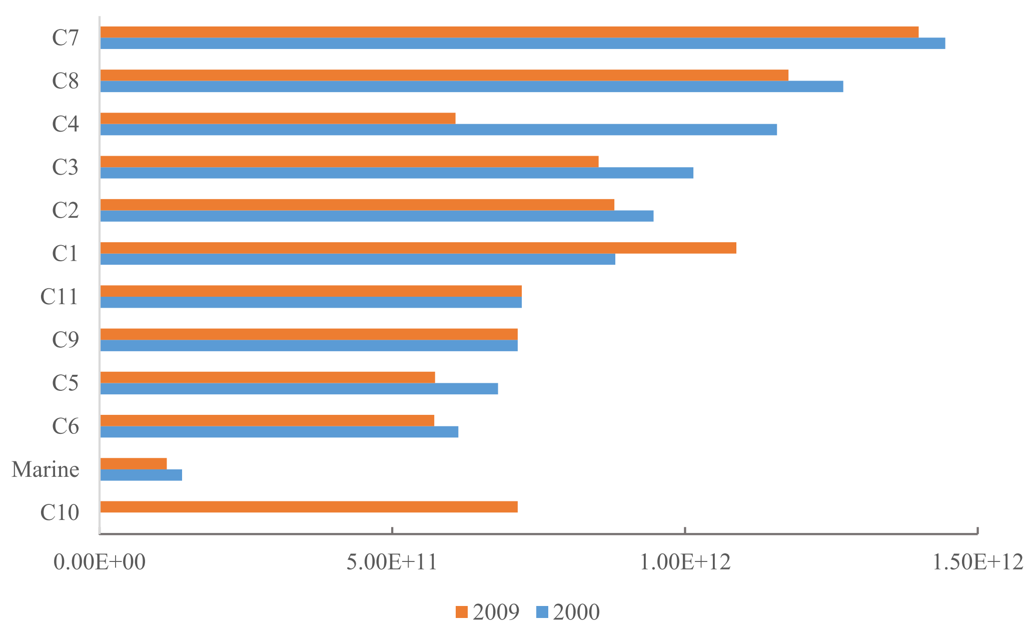

Fig. 6. PRD ESV per unit area for coastal and marine ecosystems (sej/m^2) (C1-Shallow marine waters; C2-Marine subtidal aquatic beds; C3-Coral Reefs; C4-Rocky marine shores; C5-Intertidal sand/shingle/pebble beaches; C6-Intertidal mud/sand flats; C7-Intertidal marshes; C8-Mangroves; C9-Permanent estuarine waters; C10-Estuarine systems of deltas; C11-Coastal brackish/saline lagoons; Marine: marine ecosystem).

such as lake, river ecosystem, this service should be included.

4.2.2. Advantages and limitations of accounting on biodiversity conservation

The approach shown in this study to assess the biodiversity level can avoid double counting. However, some limitations still exist. For example, more details could be included by calculating turnover time for specific species, as well as the emergy referred to the support area of each specie. With this respect, however, data inputs would be currently unavailable in the majority of cases. The second challenge would be to apply the accounting process to each taxonomic or phylogenetic group. According to Campbell and Tilley (2016), this would support the definition of species variability based on turnover times. A third limitation is that it fails to reflect the uniqueness and importance of species, such as endangered species. Finally, biodiversity should be accounted across trophic levels, applying the approach typical of system theory, considering the existing food web interactions (Brown et al., 2006).

4.2.3. Marine ecosystems water and air purification services

This study tested the assumption, in the case of marine ecosystems, of large water purification capacity for the majority of existing pollutants. The result indicates that, in the PRD area, its value was 9.25E+27 sej in 2009, being around 7 orders of magnitude larger than the other marine ESV. This result proves that the hypothesis is reasonable. However, considering the evidence of several studies, various terrestrial, marine and air pollution sources undermine the ocean health (Abessa et al., 2018). Therefore, it does not indicate that ocean ecosystem can be polluted without being worried.

With respect to air purification, the effects of marine ecosystem are often ignored. Prof. However, ocean can remove haze, being the final sedimentary area of nitrogen pentoxide, formed during fossil fuels combustion process and producing photochemical smog (Mungall et al., 2017). During nighttime, the ocean's surface absorbs nitric oxide eliminating about 15% of the smog chemicals. Specific evaluation of haze purification is still unavailable. However, this knowledge could provide the basis for further researches in related fields.

4.2.4. Inclusion of damages and losses in accounting process

Ecosystem dis-services are fairly new concepts, without a consensus on their definition. Lyytimäki et al. (2008) and Swinton et al. (2007) suggested that they can be treated as ecological functions interfered or harmed by human activities. If dis-services are measured, they should be deducted from the total ESV. Some ecological phenomena caused by human activities or natural disaster, such as seawater intrusion, typhoon, tsunami and so on, can harm ecosystems. Should we consider these phenomena as dis-services which should be reduced from the total ESV or just exclude them into services? In such a case, how could disservices be measured? These questions, which remain unaddressed in this research, would require specific efforts.

A possible reasoning is developed, using seawater intrusion as an exploratory example. According to Svensson and Theander (2013), the most common causes for seawater intrusion are pumping and sea-level rise, resulting in the groundwater level of seawater higher than that of freshwater and leading to a final seawater intrusion. This is a dis-service in coastal ecosystems. In turn, seawater intrusion causes groundwater salinization. This is another disservice, considering that mixing of freshwater bodies with <1% of seawater (250 mg/L chloride) by volume makes it non-potable (Gorchev and Ozolins, 1984). We suggest to evaluate seawater intrusion, driven by the kinetic energy of water, and the emergy required by this process as:

$$E_{msi} = \frac{1}{2} M_{sw} * v^2 * UEV_w \tag{1}$$

where: E_{msi} represents the emergy needed by seawater intrusion (sej); M_{sw} means the mass of seawater in the process of seawater intrusion (g); v is the average water velocity (m/s); $UEV_{geo,\ w}$ is assumed to be the transformity of water kinetic energy (sej/J). However, the lack of seawater intrusion data prevent from calculating this quantity.

Except for marine ecosystems, other ecosystems also generate dis-services, consuming resources and resulting in negative effects on other systems. For example, water consumption, greenhouse gases emissions and underutilized fertilizer discharge in agricultural ecosystem have adverse influence on human beings (Ma et al., 2015).

4.2.5. Advantages and limitations of the present work

Emergy-based ESV accounting method proposed in this study also have some advantages in communicating policy making relative to economic methods. To be more specific, approaches to policy start with systems overviews applying diagram including significant inputs, components and relationships (Odum, 1996). Emergy diagram of ecosystem services re-understand the generation and formation of ES, which is driven by the three renewable resources, i.e. solar, earth cycle and tidal energy (Brown and Ulgiati, 2016). It can also keep track of quantity and quality of materials, flows in systems and the interactions among system components at diverse scales (Yu et al., 2016). Whereas many economic methods rate jobs as contribution according to the money spent, only the feedback-loop design is reinforcing (see Fig. 7, Odum, 1996). That means the first merit of emergy-based ESV to communicating policy is that it can make the ecological and economic uses of ecosystem and maximize ES contribution to public welfare. The second advantage is that emergy evaluation of ESV is much cheaper and quicker than economic evaluation of ESV (Odum, 1996). For example, on an economic analysis of the alternatives for one coastal ecosystem restoration policy, $1 million may be spent on questionnaires to identify human's preferences, whereas a much more rigorous emdollar evaluation possibly could have been done for $10,000. Note that emdollar is the proportion of gross economic product due to emergy flow.

Some topics require to be addressed in the future. This is true for calculating biodiversity, as well as cultural and educational values. Further, large-scale data are necessary to improve the quality of coastal and marine ESV. However, despite these limitations, this study defines a coherent and systematic ESV accounting method, whose application can provide a solid starting pointing for the development of a decision-support system for coastal and marine ecosystem conservation and management.

5. Conclusions

The protection of coastal and marine ecosystem is urgent, due to their serious threatened situation. This paper mainly aims to establish coastal and marine ESV accounting methods to provide the basis for coastal and marine ecosystems conservation and management. A coastal and marine ESV accounting method, based on emergy analysis, is proposed to overcome the limitations of existing measurements and fill the research gap on the lack of systematic marine ESV evaluation methods. This includes ecosystem classification system, ecosystem services classification system, ESV formation mechanism and their accounting techniques.

The coastal and marine ecosystems at the PRD area (China) are

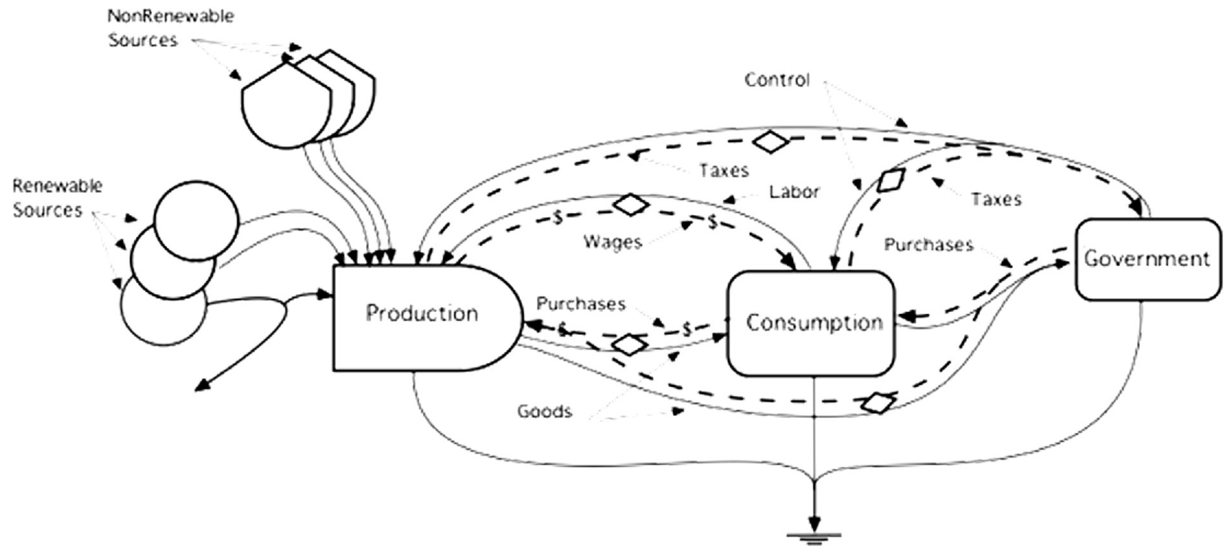

Fig. 7. Emergy diagram of ecological-economic-social complex system (Modified from Brown and Ulgiati, 2016).

selected as a study area to test the accounting method. The results indicate that the coastal and marine ESV decreased from 2000 to 2009. To be more specific, for coastal ecosystems, except for biomass increase and carbon sequestration increased, the rest ecosystem services value decreased from 2000 to 2009. Among them, water purification contributes most to the decrease, followed by soil building and climate regulation. For marine ecosystem, biomass increase and carbon sequestration decreased while the climate regulation keep stable. Also, coastal ecosystems have the largest potential to regulation climate whether at local or regional scale. Intertidal marshes have the largest ESV per square meter, followed by mangrove, coral reefs and rocky marine shores, while marine ecosystem owns the smallest ESV per square meter. These results also indicate the accounting methods on coastal and marine ESV proposed in this study can capture the spatio-temporal dynamics in evaluating ES.

Due to the uniqueness of marine ecosystem, an unlimited water purification capacity for general water pollutants is assumed in this study and the accounting result also indicate this hypothesis is reasonable. However, the exception of oil spilling or leakage should be considered, being the pollutants concentration far beyond the self-purification ability of marine ecosystem. Meanwhile, the disservices of coastal ecosystems, i.e. seawater intrusion, typhoon and tsunami would also require to be considered and deducted from the total ESV if data is available.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Abel, T., 2010. Human transformities in a global hierarchy: emergy and scale in the production of people and culture. Ecol. Model. 221, 2112–2117.
Abel, T., 2013. Emergy evaluation of DNA and culture in 'information cycles'. Ecol. Model. 251, 85–98.
Abessa, D.M.S., Albuquerque, H.C., Morais, L.G., Araújo, G.S., Fonseca, T.G., Cruz, A.C.F., Campos, B.G., Camargo, J.B.D.A., Gusso-Choueri, P.K., Perina, F.C., Choueri, R.B., Buruaem, L.M., 2018. Pollution status of marine protected areas worldwide and the consequent toxic effects are unknown. Environ. Pollut. 243, 1450–1459.
Administration, N.F.a.G., 2015. China Wetlands Resources Guangdong Volume. China Forestry Publishing House, Beijing.
Barbier, E.B., 2017. Marine ecosystem services. Curr. Biol. 27, 507–510.
Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. Ecol. Monogr. 81, 169–193.
Barbier, E.B., Koch, E.W., Silliman, B.R., Hacker, S.D., Wolanski, E., Primavera, J., Granek, E.F., Polasky, S., Aswani, S., Cramer, L.A., 2008. Coastal ecosystem-based management with nonlinear ecological functions and values. Science 319, 321–323.
Bateman, I.J., Mace, G.M., Fezzi, C., Atkinson, G., Turner, K., 2011. Economic analysis for ecosystem service assessments. Environ. Resour. Econ. 48, 177–218.
Bhagabati, N.K., Ricketts, T., Sulistyawan, T.B.S., Conte, M., Ennaanay, D., Hadian, O., Mckenzie, E., Olwero, N., Rosenthal, A., Tallis, H., 2014. Ecosystem services reinforce Sumatran tiger conservation in land use plans. Biol. Conserv. 169, 147–156.
Braat, L.C., Groot, R.D., 2012. The ecosystem services agenda:bridging the worlds of natural science and economics, conservation and development, and public and private policy. Ecosys. Serv. 1, 4–15.
Brown, M.T., 2004. A picture is worth a thousand words: energy systems language and simulation. Ecol. Model. 178 (1–2), 83–100.
Brown, M.T., Cohen, M.J., Bardi, E., Ingwersen, W.W., 2006. Species diversity in the Florida Everglades, USA: a systems approach to calculating biodiversity. Aquat. Sci. 68, 254–277.
Brown, M.T., Ulgiati, S., 2004. Energy quality, emergy, and transformity: H.T. Odum's contributions to quantifying and understanding systems. Ecol. Model. 178, 201–213.
Brown, M.T., Ulgiati, S., 2016. Emergy assessment of global renewable sources. Ecol. Model. 339, 148–156.
Buenfil, A.A., 2001. Emergy Evaluation of Water. Doctoral dissertation, University of Florida, Gainesville, USA.
Camacho-Valdez, V., Ruiz-Luna, A., Ghermandi, A., Berlanga-Robles, C.A., Nunes, P.A., 2014. Effects of land use changes on the ecosystem service values of coastal wetlands. Environ. Manag. 54, 852–864.
Campbell, E.T., 2018. Revealed social preference for ecosystem services using the eco-price. Ecosys. Serv. 30, 267–275.
Campbell, E.T., 2012. Valuing Forest Ecosystem Services in Maryland and Suggesting Fair Payment Using the Principles of Systems Ecology. The Department of Environmental Science and Technology (ENST). University of Maryland, College Park, p. 239.
Campbell, E.T., Brown, M.T., 2012. Environmental accounting of natural capital and ecosystem services for the US National Forest System. Environ. Dev. Sustain. 14, 691–724.
Campbell, E.T., Tilley, D.R., 2016. Relationships between renewable emergy storage

or flow and biodiversity: a modeling investigation. Ecol. Model. 340, 134–148.

Canu, D.M., Ghermandi, A., Nunes, P.A.L.D., Lazzari, P., Cossarini, G., Solidoro, C., 2015. Estimating the value of carbon sequestration ecosystem services in the Mediterranean Sea: an ecological economics approach. Glob. Environ. Chang. 32, 87–95.

Chester, R., Jickells, T.D., 2012. Marine Geochemistry, third ed. Blackwell Publishing, Wiley-, New Jersey.

Coates, D., 2016. Strategic Plan for Biodiversity (2011–2020) and the Aichi Biodiversity Targets.

Costanza, R., d'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the the world's ecosystem services and natural capital. Nature 387, 253–260.

Costanza, R., de Groot, R., Braat, L., Kubiszewski, I., Fioramonti, L., Sutton, P., Farber, S., Grasso, M., 2017. Twenty years of ecosystem services: how far have we come and how far do we still need to go? Ecosys. Serv. 28, 1–16.

Costanza, R., Groot, R.D., Sutton, P., Ploeg, S.V.D., Anderson, S.J., Kubiszewski, I., Farber, S., Turner, R.K., 2014. Changes in the global value of ecosystem services. Glob. Environ. Chang. 26, 152–158.

Dobson, A., Lodge, D., Alder, J., Cumming, G.S., Keymer, J., Mcglade, J., Mooney, H., Rusak, J.A., Sala, O., Wolters, V., 2006. Habitat loss, trophic collapse, and the decline of ecosystem services. Ecology 87, 1915–1924.

Ellis, J.I., Hewitt, J.E., Clark, D., Taiapa, C., Patterson, M., Sinner, J., Hardy, D., Thrush, S.F., 2015. Assessing ecological community health in coastal estuarine systems impacted by multiple stressors. J. Exp. Mar. Biol. Ecol. 473, 176–187.

Fioramonti, L., 2014. How Numbers Rule the World: the Use and Abuse of Statistics in Global Politics. Zed Books, London.

Finlayson, C.M., Everard, M., Irvine, K., McInnes, R.J., Middleton, B.A., Dam, A.A.v., Davidson, N.C., 2018. The Wetland Book. Springer, Dordrecht.

Franzese, P.P., Buonocore, E., Donnarumma, L., Russo, G.F., 2017. Natural capital accounting in marine protected areas: the case of the Islands of Ventotene and S. Stefano (Central Italy). Ecol. Model. 360, 290–299.

Gorchev, H.G., Ozolins, G., 1984. WHO guidelines for drinking-water quality. WHO Chron. 38, 104–108.

Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., 2008. A global map of human impact on marine ecosystems. Science 319, 948–952.

Han, Q., Huang, X., Shi, P., Zhang, Q., 2006. Coastal wetland in South China: degradation trends, causes and protection countermeasures. Chin. Sci. Bull. 51, 121–128.

Jenkins, C.N., Van Houtan, K.S., 2016. Global and regional priorities for marine biodiversity protection. Biol. Conserv. 204, 333–339.

Jiang, T.T., Pan, J.F., Pu, X.M., Wang, B., Pan, J.J., 2015. Current status of coastal wetlands in China: degradation, restoration, and future management. Estuar. Coast Shelf Sci. 164, 265–275.

Langan, C., Farmer, J., Rivington, M., Smith, J.U., 2018. Tropical wetland ecosystem service assessments in East Africa; A review of approaches and challenges. Environ. Model. Softw 102, 260–273.

Li, F., Hui, S.R., Song, H.L., Fang-Li, S.U., 2013. Evaluation of the services provided by the Shuangtai estuary wetland in Panjin based on emergy theory. China Environ. Sci. 33, 1454–1458 (in Chinese).

Lin, L., Liu, G., Wang, X., Wang, C., Liu, C., Casazza, M., 2018. Emergy-based provincial sustainability dynamic comparison in China. J. Environ. Account. Manag. 6, 249–260.

Lirman, D., Ault, J.S., Fourqurean, J.W., Lorenz, J.J., 2019. The coastal marine ecosystem of south Florida, United States. In: Sheppard, C. (Ed.), World Seas: an Environmental Evaluation, second ed., pp. 427–444.

Liu, B., Peng, S., Liao, Y., Long, W., 2017. The causes and impacts of water resources crises in the Pearl River Delta. J. Clean. Prod. 177, 34–45.

Lyytimäki, J., Petersen, L.K., Normander, B., Bezák, P., 2008. Nature as a nuisance? Ecosystem services and disservices to urban lifestyle. Environ. Sci. 5, 161–172.

Ma, F., Eneji, A.E., Liu, J., 2015. Assessment of ecosystem services and dis-services of an agro-ecosystem based on extended emergy framework: a case study of Luancheng county, North China. Ecol. Eng. 82, 241–251.

Manley, P.N., Horne, B.V., Roth, J.K., Zielinski, W.J., McKenzie, M.M., Weller, T.J., Weckerly, F.W., Vojta, C., 2006. Multiple Species Inventory and Monitoring Technical Guide. United States Department of Agriculture Forest Service, Washington.

Millennium Ecosystem Assessment (MEA), 2005. Ecosystems and Human Well-Being: Synthesis, Washington, D.C.

Mungall, E.L., Jpd, A., Jjb, W., Aky, L., Thomas, J.L., Blais, M., Gosselin, M., Miller, L.A., Papakyriakou, T., Willis, M.D., 2017. Microlayer source of oxygenated volatile organic compounds in the summertime marine Arctic boundary layer. Proc. Natl. Acad. Sci. U. S. A 114, 6203.

Murray, N.J., Clemens, R.S., Phinn, S.R., Possingham, H.P., Fuller, R.A., 2014. Tracking the rapid loss of tidal wetlands in the Yellow Sea. Front. Ecol. Environ. 12, 267–272.

Newton, A., Brito, A.C., Icely, J.D., Derolez, V., Clara, I., Angus, S., Schernewski, G., Inácio, M., Lillebø, A.I., Sousa, A.I., Béjaoui, B., Solidoro, C., Tosic, M., Cañedo-Argüelles, M., Yamamuro, M., Reizopoulou, S., Tseng, H.C., Canu, D., Roselli, L., Maanan, M., Cristina, S., Ruiz-Fernández, A.C., de Lima, R.F., Kjerfve, B., Rubio-Cisneros, N., Pérez-Ruzafa, A., Marcos, C., Pastres, R., Pranovi, F., Snoussi, M., Turpie, J., Tuchkovenko, Y., Dyack, B., Brookes, J., Povilanskas, R., Khokhlov, V., 2018. Assessing, quantifying and valuing the ecosystem services of coastal lagoons. J. Nat. Conserv 44, 50–65.

Odum, H.T., 1996. Environmental Accounting: Emergy and Environmental Decision Making. John Wiley & Sons Inc.

Odum, H.T., Odum, E.C., 2000. Modeling for All Scales, an Introduction to System Simulation. Academic Press, San Diego, CA (USA).

Ouyang, Z., Zheng, H., Xiao, Y., Polasky, S., Liu, J., Xu, W., Wang, Q., Zhang, L., Xiao, Y., Rao, E., Jiang, L., Lu, F., Wang, X., Yang, G., Gong, S., Wu, B., Zeng, Y., Yang, W., Daily, G.C., 2016. Improvements in ecosystem services from investments in natural capital. Science 352, 1455–1459.

Pendleton, L.H., Thébaud, O., Mongruel, R.C., Levrel, H., 2016. Has the value of global marine and coastal ecosystem services changed? Mar. Policy 64, 156–158.

Roberts, K.E., Valkan, R.S., Cook, C.N., 2018. Measuring progress in marine protection: a new set of metrics to evaluate the strength of marine protected area networks. Biol. Conserv. 219, 20–27.

Sandhu, H., Clarke, B., Baring, R., Anderson, S., Fisk, C., Dittmann, S., Walker, S., Sutton, P., Kubiszewski, I., Costanza, R., 2018. Scenario planning including ecosystem services for a coastal region in South Australia. Ecosys. Serv. 31, 194–207.

Sun, C., Wang, S., Zou, W., 2016. Chinese marine ecosystem services value: regional and structural equilibrium analysis. Ocean Coast Manag. 125, 70–83.

Sun, B., Cui, L., Li, W., Kang, X., Pan, X., Lei, Y., 2018a. A meta-analysis of coastal wetland ecosystem services in Liaoning Province, China. Estuarine. Coast. Shelf Sci. 200, 349–358.

Sun, C., Wang, Y., Zou, W., 2018b. The marine ecosystem services values for China based on the emergy analysis method. Ocean Coast Manag. 161, 66–73.

Svensson, A., Theander, J., 2013. Seawater intrusion processes, investigation and management: recent advances and future challenges. Adv. Water Resour. 51, 3–26.

Swinton, S.M., Lupi, F., Robertson, G.P., Hamilton, S.K., 2007. Ecosystem services and agriculture: cultivating agricultural ecosystems for diverse benefits ☆. Ecol. Econ. 64, 245–252.

Tallis, H., Polasky, S., 2009. Mapping and valuing ecosystem services as an approach for conservation and natural-resource management. Ann. N. Y. Acad. Sci. 1162, 265–283.

Thompson, K., Miller, K., Johnston, P., Santillo, D., 2017. Storage of Carbon by Marine Ecosystems and Their Contribution to Climate Change Mitigation, Greenpeace Research Laboratories Technical Report (Review). Greenpeace Research Laboratories, Exeter.

Turcato, C., Paoli, C., Scopesi, C., Montagnani, C., Mariotti, M.G., Vassallo, P., 2015. Matsucoccus bast scale in Pinus pinaster forests: a comparison of two systems by means of emergy analysis. J. Clean. Prod. 96, 539–548.

UNEP-WCMC and IUCN, 2016. Protected Planet Report 2016, Cambridge UK and Gland, Switzerland.

Vassallo, P., Bianchi, C.N., Paoli, C., Holon, F., Navone, A., Bavestrello, G., Cattaneo Vietti, R., Morri, C., 2018. A predictive approach to benthic marine habitat mapping: efficacy and management implications. Mar. Pollut. Bull. 131, 218–232.

Watson, M.S., Hewson, S.M., 2018. Securing protection standards for Canada's marine protected areas. Mar. Policy 95, 117–122.

Wilkinson, C., 2008. Status of the Coral Reefs of the World: 2008. Global Network and Reef and Rainforest Research Centre, Townsville, Australia, p. 296.

Xia, S., Yu, X., Millington, S., Liu, Y., Jia, Y., Wang, L., Hou, X., Jiang, L., 2017. Identifying priority sites and gaps for the conservation of migratory waterbirds in China's coastal wetlands. Biol. Conserv. 210, 72–82.

Yang, W., Jin, Y., Sun, T., Yang, Z., Cai, Y., Yi, Y., 2018. Trade-offs among ecosystem services in coastal wetlands under the effects of reclamation activities. Ecol. Indicat. 92, 352–366 .

Yang, Q., Liu, G., Brown, M., Casazza, M., Campbell, E., Gianneti, B., 2018. Development of a new framework for non-monetary accounting on ecosystem services valuation. Ecosys. Serv. 34, 37–54.

Yu, X., Geng, Y., Dong, H., Fujita, T., Liu, Z., 2016. Emergy-based sustainability assessment on natural resource utilization in 30 Chinese provinces. J. Clean. Prod. 133, 18–27.

Zheng, X., Chen, D., Wang, Q., Zhang, Z., 2014. Seawater desalination in China: retrospect and prospect. Chem. Eng. J. 242, 404–413.