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ORIGINAL PAPER

Valuation of mangrove ecosystem services based on emergy: a case study in China

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Abstract The mangrove ecosystem is a very important coastal ecosystem in China. However, the mangrove area of China has been severely reduced during the past 50 years. An important reason is that their values are not adequately represented in decision-making. Often the economic valuations of mangroves include only direct uses and products of mangroves, which only represent part of the total value of mangrove ecosystem services. Using the emergy synthesis method, this paper aims at assessing the emergy value of mangrove ecosystem services in China. The emergy synthesis method can be usefully applied to value ecosystem services from a "donor-side" perspective. It provides an eco-centric value of goods and services based on the inputs and outputs that support a system rather than the generated outputs (ecosystem services) that are useful for humans. In this study, the amounts of ecosystem services (outputs) have been converted to a common unit using the emergy synthesis method. We present a possible perspective for ecosystem service (user-side) valuation using the emergy synthesis method (donor-side approach). The ecosystem services of mangroves in China evaluated in our synthesis include organic matter production, raw materials, habitat, disturbance regulation, waste treatment and scientific research. The results show that the total emergy value of mangrove ecosystem services in China, which covers 22,752 ha, adds up to 7.56E+08 Em$ or 33,219.71 Em$/ha. The results from the valuation of selected mangrove ecosystem services suggest that mangroves are of significant importance to human well-being.

Keywords Mangrove · Ecosystem services · China · Emergy value

Introduction

Mangrove ecosystems are complex, diverse and important coastal ecosystems that provide a number of goods and services (Lugo and Snedaker 1974; Duke 1992; Ewel et al. 1998). However, deforestation and degradation are common among mangrove ecosystems all over the world (Duke et al. 2007). In China, mangrove lands have been regarded as wastelands by many, and that has resulted in nearly two-thirds of the mangroves having been lost during the past few decades (Li and Lee 1997). The estimates for the total area of mangroves in China now are only 22,752 ha (Wang and Wang 2007). Although 34 mangrove nature reserves have been established to date in China, which account for 80 % of the total estimated mangrove area of China (Chen et al. 2009), the pressures of increasing population, industrial and urban development along coast areas are still serious threats to mangroves (Wang et al. 2002; Lin 2003; Qiang and Lin 2004; Liu et al. 2006; Wang and Wang 2007). One major reason for disregarding the value of mangroves is that their full value is neither calculated nor recognized. When valuations do not measure the contributions of mangrove ecosystem, as is currently the case in China, they are not protected. This suggests that the valuation of mangrove ecosystem services is a necessary (but certainly not the only) ingredient in practical policy. More recently, there is rapidly increasing literature on methods and case studies for valuation of mangrove ecosystems

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services (Hang et al. 2000; Xin et al. 2008, 2009; Xu et al. 2010; Wang et al. 2010), and they are all focused on the monetary value. Qin et al. (2000) suggested, "Using the monetary cost of reinforcing nature as a measure of its value underestimate the wealth required for replacement, because the major free environmental contributions are not included in the cost." Odum and Odum (2000) proposed that the best way to evaluate ecosystem services is to use one kind of energy as the common denominator.

The diversity in functions that the mangrove ecosystem performs makes it an incredibly valuable ecosystem to all the species that live near the coast, including humans. By recognizing its services and the value provided to humans and other species on the coast, we must develop indicators of value which can be used in decision-making. The services of mangrove ecosystems in China, used in our synthesis, include organic matter production, raw materials, habitat, disturbance regulation, waste treatment and scientific research. The organic matter production includes leaf litter and detrital matter, which are valuable sources of food for animals in estuary and coastal waters. The raw materials are for the production of timber. The habitat is the capacity of the mangrove ecosystem to provide refuge and reproduction habitat to wild animals. The disturbance regulation is the capacity of the mangrove ecosystem to protect and stabilize the coastlines. The waste treatment services can be assessed based on the data concerning the capacity of mangroves to remove nutrients from adjacent waters. The scientific research services relate to the unlimited opportunities for scientific study. According to these six kinds of services, we applied the emergy synthesis method for quantization of mangrove ecosystems services based on the energy and/or material flow. This work was done at Zhejiang Ocean University, China, and was completed in August 2012.

Materials and methods

Emergy synthesis

Odum (1983, 1988, 1996) using the energy systems theory developed a comprehensive ecological economic evaluation method (i.e., emergy synthesis) to evaluate different energy, material and monetary flows in terms of their emergy. It provides a tool for different kinds of energy flows and materials in a system. Emergy, specifically solar emergy, is "the available solar energy used up directly and indirectly to make a service or product. Its unit is the solar emjoules (abbreviated seJ)" (Odum 1996). Solar emergy of a flow or storage is the solar energy required to generate that flow or storage. It evaluates the work previously used directly and indirectly to make a good or service. Odum (1996) defined transformity (also named unit emergy value, UEV) as, "solar transformity is the solar emergy required to make one joule of a service or product. Its units are solar emjoules per joule (seJ/J). A product's solar transformity is its solar emergy divided by its energy". It is the emergy per unit energy in units of emjoules per joule that constitutes the ratio of emergy to available energy. The units of transformity are seJ/J or solar emjoules/gram (seJ/g). As its name implies, the transformity can be used to transform a given amount of energy or mass into emergy, by multiplying the energy or mass by its transformity. Once transformities are known for a class of item, the total emergy of an item can be expressed as follows: emergy = available energy or mass of item × transformity. For comparative purposes and to provide units more familiar to the public, emergy values were expressed as emdollars (or Em$). The emdollars (Em$) value of a flow of energy material or mass is calculated by first determining the emergy of the flow and then converting to emdollars using a standard conversion factor. The conversion factor is obtained by dividing the total emergy driving an economy by the economy's gross domestic product. Emdollars are, consequently, a measure of the real wealth in a system, including not only monetary payment for human services but also the services provided by the ecosystem. Converting emergy values to emdollars has helped to communicate emergy synthesis results. The strength of emergy synthesis is its ability to evaluate directly both market and non-market goods and services, and when converted to dollars of economic product, it provides a powerful quantitative decision-making tool. Some emergy synthesis gave detailed descriptions of emergy synthesis (Odum 1996; Brown et al. 2000, 2003, 2005, 2007). Brown and Ulgiati (2004) trace development of the theory and concepts of emergy and Hau and Bakshi (2004) review the concept of emergy together with a discussion of both its conceptual strengths and criticisms by others.

Emergy valuation of mangrove ecosystem

Emergy synthesis is viewed as a "donor-side" evaluation approach because it values items based on energetic inputs as opposed to consumer preferences (Odum 1988, 1996). The use of emergy synthesis method to value ecosystem services provides a stronger basis to management policies as it ensures that the global dynamics of the biosphere is taken into proper account from a "donor-side" perspective (Ulgiati et al. 2011). The concept of the "donor-side" is the "the analysis of ecosystems that are based on the consideration of inputs" (Pulselli et al. 2011). Emergy points out the value of the natural resource in its "donor-side" essence, and its value is indicated in terms of the environmental work needed directly or indirectly to generate a resource, a good or flow of an economic product.

"Ecosystem services are the conditions and processes through which natural ecosystems, and the species that

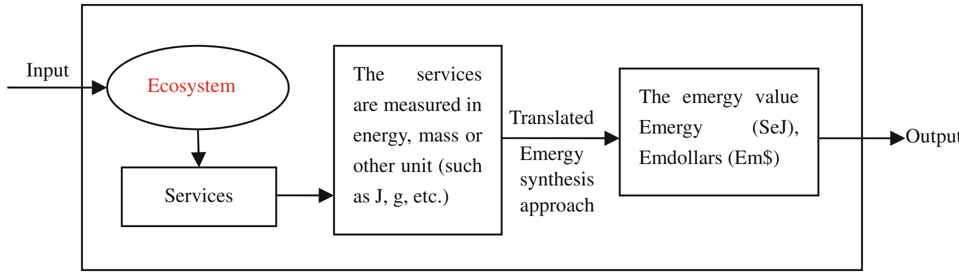

Fig. 1 The schematic valuation of ecosystem services based on emergy (modified from Pulselli et al. 2011)

make them up, sustain and fulfill human life" (Daily 1997). These functions, in turn, provide the goods and services, the outputs of the ecosystem, to be used or benefited by human and other species either directly or indirectly. Pulselli et al. (2011) identified the works to quantify these outputs (goods and services) as a "user-side" approach. Ecosystem services approach is a "user-side" approach that has recently been developed which describes ecosystems considering the useful outputs generated by them. This "user-side" approach is considerable to define the user, mainly to identify which outputs to consider and the criteria that guide this consideration. In the case of ecosystems services, the outputs of the systems are, in fact, related to the ecosystem functions, which provide services to be used by humans: This view of the use of the ecosystems means that the valuation of their services is made by means of environmental economic methodologies. These approaches most often assess only non-renewable resources, depending on what human technologies are able to extract from them (user-side) (Brown and Ulgiati 2004).

In contrast, emergy synthesis as a "donor-side" value approach, the notion of value is related to the work done by ecosystems to produce goods and services that support the economy. As Pulselli et al. (2011) pointed out that the emergy synthesis approach is not an alternative method used to value the ecosystem services, but rather a supplementary and systemic approach to highlight the mechanisms of services production by different systems. Starting with energy and matter flowing out of an ecosystem (user-side), we present our method in a very schematic way, as in Fig. 1. We use the emergy evaluation (donor-side approach) to quantify the mangrove ecosystem services (output, user-side) in China.

The services value of raw materials

Raw materials refer to renewable biotic resources such as wood and fibers for building and biochemical or biodynamic compounds for all kinds of industrial purposes (de Groot et al. 2002). The wood from mangroves is known for being rot resistant and insect resistant, making it an outstanding construction material. It is also used as raw material for the wood-based industry of various types including board mills and rayon mills. The extraction of timber is a center for economic activity. Human development has heavily used the mangrove timber as a source of wood for the construction of houses, boats, fishing poles, traps, matting, scaffolds, charcoal production and handicraft products. Mangrove timber commands a high value, so we use the emergy value of the timber yield as one part of the services value of raw materials.

The organic matter production includes leaf litters, which are valuable sources of food for animals in estuary and coastal waters and are another part of the services of raw materials. Leaves make a substantial contribution to the total litter fall in many tropical and subtropical mangroves. So, leaf litters can be considered an output of organic matter production.

The services value of habitat

Mangrove ecosystems support many types of plants and animals. The majority of plants are evergreen trees, although deciduous trees, perennial and evergreen shrubs, epiphytes, parasites and climbers, perennial grasses, palms and perennial ferns are also common constituents, together with algae, fungi and microflora. Micro- and macroscopic, terrestrial and aquatic (marine and freshwater), temporary and residential wildlife are all supported by mangroves, forming a heterogeneous habitat. They are very important as coastal habitats for commercially important fish and invertebrates. They are often referred to as nursery grounds for larval shrimp and many fish species. Mangrove forests also provide a number of ecological benefits including protecting inland structures, supporting coastal fisheries for fish and shellfish through direct and indirect food support and provisions for habitat and support of wildlife populations including a number of wading birds and sea birds. Mangrove forests are prime nesting and feeding sites for hundreds of bird species and offer well stocked "arrival and departure" facilities for hundreds of migratory species on their flights across oceans.

The service value of disturbance regulation

The disturbance regulation of the mangrove ecosystem relates to the ability to ameliorate "natural" hazards and disruptive natural events. Mangroves have a variety of key features that contribute to their resilience to disturbance (Alongi 2008). Mangrove ecosystems play an essential role in the regulation in coastal zones. Hurricanes and other coastal storms cause wind damage and flooding. Mangroves can help dissipate the force and lessen the damage of coastal storms. Mangrove communities protect shorelines during storm events by absorbing wave energy and reducing the velocity of water passing through the root barrier. Mangrove-covered shorelines are less likely to erode, and will erode significantly more slowly, than unvegetated shorelines during periods of high wave energy. In recognition of these important services, the capacity of mangroves to protect adjacent areas from storms can be measured by the wave intensity in the mangrove shoreline and by estimating the value of the possible damages if the shoreline area did not have the mangroves to protect them. We can then calculate the value of this service based on the wave current in the region. This paper includes emergy of the services value of disturbance regulation.

The service value of waste treatment

Waste treatment refers to the activities required to ensure that waste has the least practicable impact on the environment. To a limited extent, ecosystems are able to deal with the loss of nutrients, recapture excessive or external nutrients and the removal or degradation of compounds.

The waste treatment services of the mangrove ecosystem are represented mainly in the following two aspects: (a) the absorption of heavy metal and (b) the recycling of nutrients. There are several studies on heavy metals uptake by mangroves (Zheng et al. 1996a, b; Nazli and Hashim 2010). They reported that the concentrations of the heavy metals in the roots and stems of mangrove plants exceeded the other parts. The roots and stems are more difficult for grazing animal to access. Therefore, pollutants and heavy metals which the mangrove absorb are stored in the less accessible parts used by grazing animal consumption, thereby reducing the risk of heavy metals to secondary consumers. Mangroves therefore played a role in cleaning up the environment when trees were harvested and removed from the coast. Organic nutrients, including those from humans and animal waste, are often also trapped along with sediment by mangroves. Mangroves provide detrital nutrient input into coastal waters that support coastal fauna. Moreover, mangroves are an important source of nutrient flow into coastal waters. The emergy value equivalent to the level of heavy metals absorption and nutrient retention can be derived for the mangrove ecosystem services of waste treatment.

The service value of scientific research

Mangrove ecosystems are vital sources of inspiration for science, culture and art and provide many opportunities for education and scientific research. As de Groot et al. (2002) put it previously: "… environmental education" (e.g., through excursions) and function as "field laboratories" for scientific research, leading to thousands of publications each year. Natural areas also serve as important reference areas for monitoring environmental change." Here, the number of published papers (only in Chinese) about the mangrove is used as a replacement to measure the scientific research value. The emergy value of these published papers is represented as the scientific research value of mangrove ecosystem.

Results and discussion

Mangroves in China as a case study

China has limited mangrove resources of which nearly two-thirds have been lost during the past 40 years. There are 12 families, 16 genera, 27 species and 1 variety of mangroves occupying a total estimated area of 22,752 ha in China (Chen et al. 2009). Mangroves in China are naturally distributed in the province of Hainan, Guangdong, Guangxi, Taiwan, Fujian, Zhejiang, Hong Kong and Macau. The distribution of mangroves is shown in Fig. 2, and estimates of mangrove area by region appear in Table 1.

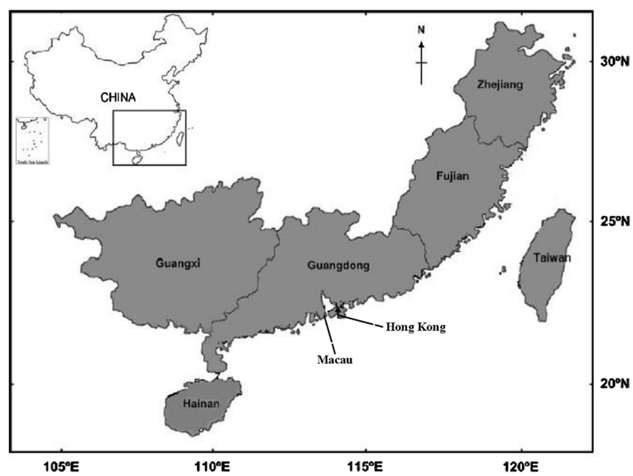

Fig. 2 The distribution of mangroves in the coast along Hainan, Guangxi, Guangdong, Fujian, Zhejiang Provinces, Macau, Hong Kong and Taiwan

Table 1 Mangrove distributions and their area in China (Wang and Wang 2007)

Mangrove community	Distributions	Area (ha)
K. candel	Macau, Hong Kong, Zhejiang, Taiwan, Fujian, Guangdong	10,447
R. stylosa	Guangxi	8,375
B. sexangula	Hainan	3,930
Total		22,752

Table 2 Emergy synthesis of mangrove ecosystem services in China

Type of ecosystem services	Raw data	Emergy per unit (seJ/unit)	Solar emergy (seJ)	Emdollars (Em$)	Emdollars value/ha (Em$/ha)	Emergy (%)
Litter[a]	3.44E+15 J	13,285	4.57E+19	6.34E+06	278.75	0.84
Timber[b]	1.45E+15 J	14,684	2.13E+19	2.96E+06	130.08	0.39
Habitat[c]	685 species	5.55E+18	3.80E+21	5.28E+08	23,220.34	69.90
Disturbance regulation[d]	1.97E+16 J	3.06E+04	6.02E+20	8.36E+07	3,672.71	11.06
Waste treatment[e]			8.42E+20	1.17E+08	5,142.93	15.48
Scientific research[f]	182	6.99E+17	1.27E+20	1.76E+07	774.89	2.33
Total			5.44E+21	7.56E+08	33,219.71	100.00

All emergy values in this paper were calculated using the baseline of 9.44 E+24 seJ/year

Emergy to money ratio = 7.20E+12 seJ/$, The data are taken from Jiang et al. (2008). Converted to 9.44E+24 seJ/year baseline from 15.83E+24 seJ/year

[a] Litter (J) (Odum et al. 2000, Folio 3, p. 60) = litter (g/m^2) × area (m^2) × 4,139 (cal/g) × 4.186 (J/cal) = 3.44E+15 J. Transformity (seJ/J) (Odum et al. 2000 Folio 3, p. 60) = 13,285 seJ/J

[b] Raw materials (timber) (Odum et al. 2000, Folio 3, p. 60) = annual output of trunk (g/m^2) × area (m^2) × 4,139 (cal/g) × 4.186 (J/cal) = 1.45E+15 J. Transformity (the biomass growth substituted for timber) (seJ/J) (Odum et al. 2000, Folio 3, p. 60) = 14,684 seJ/J

[c] Habitat (seJ): species number × transformity = 685 × 5.55E+18 = 3.80E+21 seJ. Transformity = transformity of species (1.26E+25 seJ) (Lan et al. 2002, p. 253) × the mangrove area percentages of world area (4.41E−07) = 5.55E+18

[d] Disturbance regulation (J) = coastline length (m) × 0.125 × density (kg/m^3) × gravity (m/s^2) × velocity (m/s) × (wave height)^2 (m^2) × 3,154 × 10^4(s/a)/wave period (s) = 2,275,200 × 0.125 × 1.03 × 1,000 × 9.8 × (9.8 × 0.6)$^{1/2}$ × 0.6^2 × 3,154 × 10^4/4=1.97E+16 J. Transformity = 3.06E+04 seJ/J (Odum et al. 2000, Folio 1)

[e] See Tables 3 and 4. The solar emergy value of heavy metal and nutrient is 3.86E+17 and 8.42E+20 seJ, respectively. The total is 8.42E+20 seJ

[f] Scientific research (seJ) = publication paper number (10 years average) × transformity (seJ/unit) = 182 × 6.99E+17 = 1.27E+20 seJ. Transformity (seJ/unit) = 6.99E+17 (Chen 2007)

Table 3 Emergy value of four heavy metal elements in three typical mangrove communities

Type	The annual uptake of heavy metal (mg/m^2 a)[a]			Total (g/a)	Specific emergy (seJ/g)[b]	Emergy (seJ)
	K. candel	*R. stylosa*	*B. sexangula*			
Area (m^2)	104,470,000	83,750,000	39,300,000			
Cu	10.17	1.35	1.35	1,228,577.4	6.80E+10	8.35E+16
Mn	2,268.16	53.69	53.69	243,561,229.7	8.90E+08	2.17E+17
Zn	49.14	8.8	8.8	6,216,495.8	1.25E+10	7.77E+16
Pb	4.32	1.61	1.61	649,420.9	1.25E+10	8.12E+15
Total				2.52E+08		3.86E+17

[a] The data are taken from Zheng et al. (1996a, b)

[b] The data are taken from Lan et al. (2002, pp. 76, 233)

According to the emergy synthesis, the emergy value and emdollars of the six kinds of mangrove ecosystem services were calculated. The detailed calculations are shown in Tables 2, 3 and 4.

The services value of organic matter production and raw materials

The main standing stock of China's representation of three kinds of mangrove communities, that is, *Kandelia candel*, *Rhizophora stylosa* and *Bruguiera sexangula* leaf litter productions were 920.8, 631.3 and 1,255 g/m^2 a, respectively (Lin 1997). According to the emergy synthesis (Table 2), China's mangrove ecosystem emergy value of litter was 4.57E+19 seJ, the emdollars value was 6.34E+06 Em$ and 278.75 Em$/ha, respectively. The three kinds of mangrove communities' annual timber productions were 526, 139.8 and 435.1 g/m^2, respectively (Lin 1997). The emergy value was 2.13E+19 seJ, and the emergy dollar value was 2.96E+06 Em$ (Table 2). Emdollars value of leaf litter and timber accounted for only 0.84 and 0.39 % of total emdollars value, respectively.

Table 4 Emergy value of nutrition elements in three typical mangrove communities

Type	The annual nutrition uptake(g/m^2 a)[a]			Total (g/a)	Specific emergy (seJ/g)[b]	Emergy (seJ)
	K. candel	*R. stylosa*	*B. sexangula*			
Area (m^2)	104,470,000	83,750,000	39,300,000			
N (g/m^2 a)	840	700	750	1.76E+11	3.80E+9	6.68E+20
P (g/m^2 a)	110	70	100	2.13E+10	3.90E+9	8.30E+19
K (g/m^2 a)	500	170	410	8.26E+10	1.10E+9	9.08E+19
Total				2.80E+11		8.42E+20

[a] The data are taken from Lin (2001)

[b] The data are taken from Lan et al. (2002, p. 76)

The services value of habitat

Mangrove habitats play host to a moderate number of species including 299 host benthos and fish species, 26 zooplankton species, 142 insect species, 201 bird species, 10 mammal species and 7 reptile species in China (Lin 1997). In this paper, the mangrove emergy value of these 685 species was represented in the services value of habitat. The emergy value of habitat was 3.80E+21 seJ, the emdollars value and emdollars value per unit were 5.28E+08 Em$ and 23,220.34 Em$/ha, respectively (Table 2). The emdollars value of habitat services accounted for as much as 69.90 % of total emdollars value.

The service value of disturbance regulation

In our calculation, the width of the mangroves along the coast was 100 m; the length of protected coastline of the mangrove ecosystems in China is 2,275.2 km; the average wave height was 0.6 m and the wave cycles were 4 s (Data sources: http://www.coi.gov.cn/hygb/hyhj/1998/index.html). We estimated the emergy value of disturbance regulation to be 6.02E+20 seJ, the disturbance regulation to be the worth 8.36E+07 Em$ and 3,672.71 Em$/ha (Table 2).

The service value of waste treatment

The services of waste treatment can be derived from the heavy metals absorption and nutrient retention. The total emergy value and the services annual value of mangrove waste treatment in China have been estimated to be 8.42E+2 seJ and 1.17E+08 Em$, respectively (Tables 3, 4).

The service value of scientific research

We searched published papers at website http://www.edu.cnki.net/newweb/ using mangrove as a keyword from 2001 to 2010. There were 1,816 papers total and an annual average of 181.6 papers. We estimated that the emergy value of scientific research was 1.27E+2 seJ, and the emdollars value was 1.76E+07 Em$ (Table 2).

The total service value of mangrove ecosystem in China

As mentioned above, China's mangrove ecosystem emdollars of litter was 6.34E+06 Em$, accounted for 0.84 % of total emdollars value; emdollars of timber productions was 2.96E+06 Em$, accounted for 0.39 % of total emdollars value; emdollars of habitat was 5.28E+08 Em$, accounted for 69.90 % of total emdollars value; emdollars of disturbance regulation was 8.36E+07 Em$, accounted for 11.06 % of total emdollars value; emdollars of waste treatment was 1.17E+08 Em$, accounted for 15.48 % of total emdollars value; emdollars of scientific research was 1.76E+07 Em$, accounted for 2.23 % of total emdollars value, annually. The results show that the total value (emdollars) of the mangrove ecosystem services in China, which covers 22,752 ha, add up to 7.56E+08 Em$. The emdollars value was 33,219.71 Em$/ha (Table 2).

There are two broad reasons for engaging in valuation exercises of ecosystem services: first, to show that environmental issues are important for planning at the macroeconomic level (i.e., in the consideration of the damage and depreciation of natural resource stocks in national accounts) and, second, for making efficient allocation decisions at the microeconomic level; that is, understanding the full costs and benefits of a project is essential to making investment decisions and for the decision-making process. Sufficient valuation of ecosystem services can assist decision-makers in better managing ecosystems so they can continue providing valuable services. In the past three decades, the valuation of ecosystem services has become one of the most important areas in ecological economics, and the number of papers is rising exponentially (Fisher et al. 2009). One approach is the emergy synthesis method developed by Odum (1996) for quantifying and valuing ecosystem services. The emergy synthesis method has been established as a way to properly value ecosystem services, but has also been widely criticized (Cleveland et al. 2000; Herendeen 2004; Hammond 2007). "This criticism stems from the fact that economics places an anthropocentric value on the goods and services that are generated from natural and human systems" (Voora and Thrift 2010). The emergy synthesis method, as a "donor-side" approach, provides an eco-centric value based on the inputs that support a system rather than the output (ecosystem services) that is useful for humans, might not be correct to value the ecosystem services (Herendeen 2004; Pulselli et al. 2011). In this paper, the energy and matter that is related to the ecosystem services (output) was translated to a common emergy unit seJ using the emergy synthesis method. This approach presents a possible perspective to use the emergy synthesis method (donor-side approach) valuing the ecosystem services (user-side).

A major advantage with emergy synthesis is the possibility of measuring resource use of ecosystems. It has to be acknowledged, however, that the complexity of ecosystems will always make calculations of transformities difficult and uncertain. Estimating how much of any mass or energy might have been needed to produce another in the distant past is not an easy task (Hau and Bakshi 2004). One transformity cannot acquire the emergy value of one class of goods or services. There is no single transformity for any class of product or process and that when examined in detail, each production pathway for any given product represents a unique transformation process that will result in a different transformity. Odum (1996) recognizes this shortfall and agrees that each individual product or service will have a unique transformation process. This problem is partially circumvented by deriving a range of transformities for a given product. This will affect the reliability of conclusions at high levels of detail. The emergy synthesis is developed out of theories in ecosystem ecology. Some of these theories are new and controversial hypotheses. Only further research involving emergy synthesis and system principles will verify the solidity of our calculations.

Based on the results discussed in section three, the mangrove ecosystem in China had a high value. With various ecosystem services of organic matter production, raw materials, habitat, disturbance regulation, waste treatment and scientific research, the emdollars value of mangrove in China were estimated at 7.56E+08 Em$ or 33,219.71 Em$/ha. This figure would have been higher if the values of a number of other services, such as transport and tourism, had been estimated. Due to the unavailability of data on these values, the estimated emergy values in this research only partially reflect some values of mangrove in China. However, with this partial estimation alone, there was sufficient evidence to support that this ecosystem is of significant importance to the country as a whole.

As the interface between the land and the sea, coastal mangrove areas are important not only as a source of forest and aquatic products but also play an important role in the protection of the coastal environment. The product derived directly or indirectly from the mangrove ecosystem generates many benefits to the country, and if managed more wisely than at present, such benefits could be sustainable. From our calculations, we can see that the emergy value of the absorption of a variety of nutrients and heavy metals is high, especially nitrogen, phosphorus and potassium elements, which have been identified as the key nutrients nearshore, and lead to blooms of microalgae and red-tide microorganisms. Although from the events, whose actual studies have not yet been observed, we could forecast that the planting of mangroves could be used as an effective way to prevent the occurrence of red tide.

In addition, mangroves provide habitats for plenty of plants and animals (a variety of birds, estuarine fish and terrestrial mammals) which are another major value to people and biodiversity in general. Especially, it is the prime nesting and feeding sites for hundreds of bird species and offer well stocked "arrival and departure" facilities for hundreds of migratory birds on their flights across Chinese territory. In our calculations, the proportion of habitat value of mangrove services in total value is 69.90 %, exceeding the proportion of waste treatment. Therefore, the most important services of the mangrove ecosystem in China are coastal habitats functions for various species.

Conclusion

Through a study of the matter and energy flows and using the method of emergy synthesis, this paper estimates the emergy value of mangrove ecosystems in China. One major observation emerging from the study is that mangroves are an extremely valuable forest ecosystem. This study has shown that the emergy value of mangroves is highly significant, which implies that maintenance of mangroves should receive a high priority in development policy and planning. While our calculations are rough, they highlight the need for more research both on the physical productivity of the mangrove-dependent systems and on their contribution to the local economy. This must be complemented with further studies on the impact of incremental changes in the ecosystems and their productivity due to decreased river flow, overuse, pollution and other pressures. We are still far from understanding energy flows in mangrove environments and how the mangroves connect with other ecosystems. This information could lead to better estimates of the values of the goods and services provided by the mangroves and their contribution to the regional and national economy.

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References

Alongi DM (2008) Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. Estuar Coast Shelf Sci 76(1):1–13

Brown MT, Ulgiati S (2004) Energy quality, emergy, and transformity: H.T. Odum's contributions to quantifying and understanding systems. Ecol Model 178(1–2):201–213

Brown MT, Brandt-Williams SL, Tilley D, Ulgiati S (2000) Emergy synthesis 1: theory and application of the emergy methodology. University of Florida, Gainesville, FL

Brown MT, Odum HT, Tilley D, Ulgiati S (2003) Emergy synthesis 2: theory and applications of the emergy methodology. University of Florida, Gainesville, FL

Brown MT, Bardi E, Campbell DE, Comar V, Huang SL, Rydberg T, Tilley D, Ulgiati S (2005) Emergy synthesis 3: theory and applications of the emergy methodology. University of Florida, Gainesville, FL

Brown MT, Bardi E, Campbell D, Comar V, Huang SL, Rydberg T, Tilley D, Ulgiati S (2007) Emergy synthesis 4: theory and applications of the emergy methodology. University of Florida, Gainesville, FL

Chen D (2007) Study on emergy evaluation of Guangzhou national agricultural science and technology area. Doctoral dissertation, Hunan Agricultural University

Chen LZ, Wang WQ, Zhang YH, Lin GH (2009) Recent progresses in mangrove conservation, restoration and research in China. J Plant Ecol 2(2):45–54

Cleveland CJ, Kaufmann RK, Stern DI (2000) Aggregation and the role of energy in the economy. Ecol Econ 32(2):301–317

Daily GC (ed) (1997) Nature's services: societal dependence on natural ecosystems. Island Press, Washington, DC

de Groot RS, Wilson MA, Bouman RMJ (2002) Typology for the classification, description and valuation of ecosystem services, goods and services. Ecol Econ 41(3):393–408

Duke N (1992) Mangrove floristics and biogeography. In: Robertson AI, Alongi DM (eds) Tropical mangrove ecosystems. American Geophysical Union, Washington, DC

Duke NC, Meynecke JO, Dittmann S, Ellison AM, Anger K, Berger U, Cannicci S, Diele K, Ewel KC, Field CD, Koedam N, Lee SY, Marchand C, Nordhaus I, Dahdouh-Guebas F (2007) A world without mangroves? Science 317:41–42

Ewel KC, Twilley RR, Ong JE (1998) Different kinds of mangrove forests provide different goods and services. Glob Ecol Biogeogr Lett 7(1):83–94

Fisher B, Turner RK, Morling P (2009) Defining and classifying ecosystem services for decision making. Ecol Econ 68(3):643–653

Hammond G (2007) Emergy and sustainability in a complex world: reflections on the ideas of Howard T. Odum. Int J Energy Res 31(12):1105–1130

Hang WD, Gao XM, Lu CY (2000) The ecological values of mangrove ecosystems in China. Ecol Sci 19(1):40–46 (in Chinese)

Hau JL, Bakshi BR (2004) Promise and problems of emergy analysis. Ecol Model 178(1–2):215–225

Herendeen RA (2004) Energy analysis and EMERGY analysis—a comparison. Ecol Model 178(1–2):227–237

Jiang MM, Zhou JB, Chen B, Chen GQ (2008) Emergy-based ecological account for the Chinese economy in 2004. Commun Nonlinear Sci 13(10):2337–2356

Lan SF, Qin P, Lu HF (2002) Emergy analysis of ecological economic systems. Chemical Industry Press, Beijing (in Chinese)

Li MS, Lee SY (1997) Mangroves of China: a brief review. For Ecol Manag 96(3):241–259

Lin P (1997) Mangrove ecosystem in China. Science Press, Beijing

Lin P (2001) A review on the mangrove research in China. J Xiamen Univ (Nat Sci) 40(2):592–603 (in Chinese with English abstract)

Lin P (2003) The characteristics of mangrove wetlands and some ecological engineering questions in China. Eng Sci 5(6):33–41 (in Chinese with English abstract)

Liu JC, Yan CL, Macnair MR (2006) Distribution and speciation of some metals in mangrove sediments from Jiulong River estuary, People's Republic of China. Bull Environ Contam Toxicol 76(5):815–822

Lugo AE, Snedaker SC (1974) The ecology of mangroves. Annu Rev Ecol Syst 5:39–64

Nazli MF, Hashim NR (2010) Heavy metal concentrations in an important mangrove species, *Sonneratia caseolaris*, peninsular Malaysia. Environ Asia 3(1):50–55

Odum HT (1983) Systems ecology. Wiley, New York

Odum HT (1988) Self-organization, transformity, and information. Science 242:1132–1139

Odum HT (1996) Environment accounting: emergy and environment decision making. Wiley, New York

Odum HT, Odum EP (2000) The energetic basis for valuation of ecosystem services. Ecosystems 3(1):21–23

Odum HT, Brown MT, Williams SB (2000) Handbook of emergy evaluations folios 1–4. University of Florida, Gainesville, FL

Pulselli FM, Coscieme L, Bastianoni S (2011) Ecosystem services as a counterpart of emergy flows to ecosystems. Ecol Model 222(16):2924–2928

Qiang N, Lin YG (2004) Characteristics of quantitative distribution and species composition of fouling fauna in Dongwan mangrove stands of Fangchenggang, Guangxi. J Trop Oceanogr 23(1):64–68 (in Chinese with English abstract)

Qin P, Wong YS, Tam NFY (2000) Emergy evaluation of Mai Po mangrove marshes. Ecol Eng 16(2):271–280

Ulgiati S, Zucaro A, Franzese PP (2011) Shared wealth or nobody's land? The worth of natural capital and ecosystem services. Ecol Econ 70(4):778–787

Voora V, Thrift C (2010) Using emergy to value ecosystem goods and services. International Institute for Sustainable Development, Winnipeg

Wang WQ, Wang M (2007) The mangroves of China. Science Press, Beijing (in Chinese)

Wang BS, Liao BW, Wang YJ (2002) Mangrove forest ecosystem and its sustainable development in Shenzhen Bay. Science Press, Beijing (in Chinese)

Wang Y, Li SS, Sun RY, Wang Y (2010) Valuation of ecological service function of Futian mangroves and birds national nature reserve, Shenzhen. J South China Norm Univ (Nat Sci) 3(8):86–91 (in Chinese)

Xin K, Huang X, Zhang SP (2008) Assessment of ecological functions of mangrove wetland in Dongzhai Port of Hainan. Wetl Sci Manag 4(4):28–31 (in Chinese)

Xin K, Huang X, Hong ML, Liu Q, Lan CG (2009) Analysis and valuation of mangrove ecosystem function. Ecol Econ 3(1):140–142 (in Chinese)

Xu SN, Li SY, Chen ZZ (2010) The habitat functions of mangroves for aquatic fauna and fisheries. Acta Ecol Sin 30(1):186–196 (in Chinese)

Zheng WJ, Zheng FZ, Lian YW (1996a) Accumulation and dynamics of Cu, Pb, Zn and Mn elements in *Kandelia candel* druce mangrove community of Jiulong River estuary of Fujian. Acta Bot Sin 38(3):227–233 (in Chinese)

Zheng WJ, Lian YW, Zheng FZ, Lin P (1996b) Accumulation and dynamic of heavy metal elements in *Rhiziphora stylosa* community at Yingluo bay in Guangxi. Acta Phytoecol Sin 20(1):20–27 (in Chinese)