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Conservation and economic viability of nature reserves: An emergy evaluation of the Yancheng Biosphere Reserve

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ABSTRACT

Evaluating the ecological and economic benefits of nature reserves in a fair way is a difficult problem confronting not only conservation scientists and managers but also governments and private land owners. Nature reserves and other social and economic land uses must be evaluated on an objective basis to provide an accurate measure of relative benefits for decision-making. The ecological and economic benefits of various land uses can be expressed in equivalent terms using emergy as a common denominator. Emergy synthesis is a biophysical, donor-based method of valuation that we used to assess the ecological-economic system of the Yancheng Biosphere Reserve (YBR) in North Jiangsu Province, China. In this paper, we introduce new emergy measures designed especially to capture the conservation value of natural lands, as well as a measure of the economic viability of nature reserves. The network structure of natural resources, economic production, and conservation activities in Yancheng reserve was examined and compared to the Maipo Nature Reserve (MNR) in Hong Kong, and a salt marsh ecological-engineering system also in Yancheng. This study showed that there is about a 10:1 return on the emergy invested by government in operating the Yancheng Biosphere Reserve, which is a major migratory stop-over and wintering site for the endangered red-crowned crane (*Grus japonensis*). Only 2.2% of the support for conservation in YBR comes from the private sector compared to 41.4% for MNR. One way to improve social self-sufficiency of the reserve is to develop ecotourism and private donors, which will increase economic vitality and mitigate the intense economic competition for reserve land.

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1. Introduction

Wetlands are among the most productive ecosystems on Earth (Matthews, 1984; Zhao, 2002), and in many places around the world these ecosystems are being pressured by rapid population growth and economic development. Establishing wetland reserves has been shown to be an efficient method for conservation of these ecosystems, because wetland species are protected through the preservation of typical wetland habitats (Kessler and Thomas, 2006). The Yancheng Biosphere Reserve is the first and largest tidal-flat, nature reserve in China. However, expanding economic development

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in the region is causing more and more of its area to be converted to other land uses, e.g., agriculture and aquaculture. This situation is not unique to China, as evidenced by the fact that between 50% and 100% of strictly protected areas in South America and Asia are reported to be used or occupied by people (Brockington et al., 2006). Many of the public land conflicts and ecological problems of the last century arose because resource management decisions failed to balance social, economic, and ecological objectives (Leough and Blahna, 2006). According to Folke (2006), ecosystem management must move away from perspectives that pretend people can be separated from nature, because conservation cannot be achieved without making decisions that are ecologically sustainable, socially acceptable and economically feasible. To achieve this target, two urgent questions confront conservation managers of the Yancheng Biosphere Reserve, other nature reserves, and local governments all over the world, (1) "How can we make full use of limited and highly productive coastal areas to fulfill the needs of both conservation and local economic development?", and (2) "How can the productive value of natural wetland resources be assessed and compared to the value of the developed lands in a fair manner?"

Since the 1980s, many methods have been used to determine the value of wetland ecosystems and reserves. As a consequence, a large literature exists, especially for economic methods that directly determine the market value of wetland products (Ouyang and Zhao, 2004). Also, various methods have been used to estimate economic value by indirect means based on the willingness to pay, including avoided cost, replacement cost, factor income, travel cost, contingent valuation and public deliberation valuation (Costanza et al., 1997; Acharya, 2000; Woodward and Wui, 2001). Because of the subjective nature of these valuations, and the often weak linkages between them and the material processes and mechanisms of ecosystems, the variability of assessment results among methods is large, and arguments about detailed accounting methods and techniques are still on-going (Costanza et al., 1998; Pimentel, 1998; Turner et al., 1998). It has been difficult for some people to accept the results of ecological-economic assessments without seeing a plausible integration of ecological functions and economic principles within the evaluation methodology (Drechsler and Watzold, 2001). The goal of integrated thinking is to frame the conservation and management questions correctly from the start through cooperation and consultation between scientists in both ecological and economic disciplines (Chee, 2004; Watzold et al., 2006).

Environmental accounting using emergy (Odum, 1996) overcomes many of the subjective shortcomings of neoclassical valuation methods mentioned above by using an objective quantity, solar emergy to count in equivalent units all the energy of different kinds required directly and indirectly to create economic and environmental products and services. The emergy of a product or service is defined as all the available energy of one kind used up directly or indirectly in the production process (Odum, 1996). Its unit (Scienceman, 1987) is the solar emjoule (sej). Emergy synthesis is a donor-based valuation method that is not dependent on the subjective value assigned by people and thus it can be an independent alternative to economic valuation. Publications centered on emergy synthesis are appearing with increasing frequency in the scientific literature to address problems that require integrated ecological-economic evaluation (Odum, 1988; Tilley and Swank, 2003). Beginning with the evaluation of marshes (Odum, 1996; Odum and Hornbeck, 1997; Odum and Odum, 2000), emergy theory and synthesis methods have been successfully used to evaluate wetland ecosystems (Odum, 1996; Brown and McClanahan, 1996; Qin et al., 2000; Nelson et al., 2001; Martin, 2002; Lu et al., 2002a; Tilley and Swank, 2003; Zuo et al., 2004). However, from our review of the literature, we found that additional indices were needed to evaluate the ecological-economic effects of conservation decisions.

In this study, emergy indices calculated from an analysis of the network structure of the system were used to assess the effects of economic development and conservation actions. A new quantity, conservation value (CV), was defined to capture the ecological and economic benefits of conservation specifically. Conservation value includes not only the change in renewable natural capital but also the change in nonrenewable assets of the wetland and the contributions of the wetland system to its larger regional and global systems. The definition and documentation of conservation value is a key factor in fully assessing the contributions of natural lands to society.

A new index, the social self-sufficiency ratio (SSR), was defined to show the extent to which contributions from the private sector sustain reserve operations, i.e. we examined the question, "Is the emergy that can be purchased with economic revenues generated from the reserve sufficient to supply all of the emergy needed to manage it?" In addition, to evaluate the effectiveness of investment in nature reserves comprehensively and to assess their sustainability, four existing emergy indices were modified to include conservation value.

2. Location and study sites

Yancheng Biosphere Reserve (32°34′–34°28′N, 119°48′–121°56′E) is an alluvial plain and beach area, located in Jiangsu Province to the east of Yancheng city (Fig. 1). It lies in the transition belt between warm temperate and northern subtropical zones and as a result the reserve's climate is controlled by seasonality, with a dry, cold winter, and a hot, rainy summer. The length of the coastline is 582 km, with a 12 h and 26 min interval between high semidiurnal tides (Liu and Luan, 2000; An, 2003). The Yancheng reserve is the largest over-wintering site for the red-crowned crane (*Grus japonensis*). It is also a stop-over site for over 300 species of migratory birds (Zhu et al., 2004). The Yancheng reserve is a vital part of China's system for the conservation of both biodiversity and coastal wetland ecosystems.

The original vegetation of the Yancheng reserve was comprised of *Suaeda salsa* (L. Pall.) and common reed (*Phragmites communis* Trin.). In 1963 and 1979, common cordgrass (*Spartina anglica* C.E. Hubbard) and smooth cordgrass (*Spartina alterniflora* Loisel) were introduced from England and the United States, respectively, and after the 1990s, they became the two dominant plants of the intertidal zone in Jiangsu Province (Chung, 1994; Li et al., 2005). Since 1981, the tidal lands have

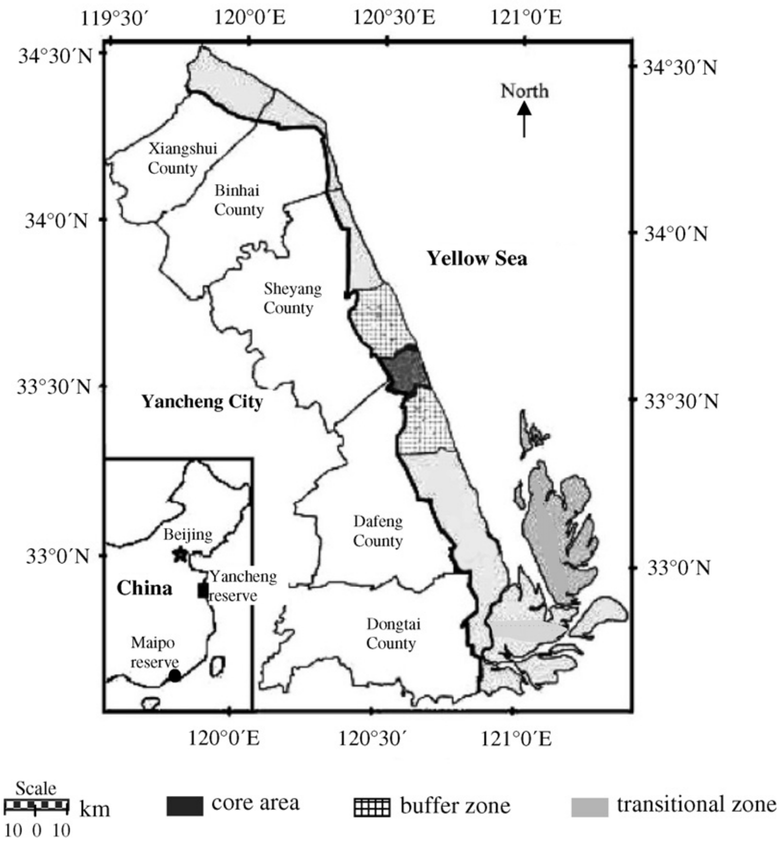


Fig. 1 – Location of the Yancheng Biosphere Reserve showing the core, buffer and transitional zones and the Maipo Nature Reserve (modified from Zuo et al., 2004).

been exploited intensely by local people for economic aims, which led to a rapid decrease in the populations of rare waterfowl and wading birds found in the area (An, 2003). Regulations to reconstruct the vegetation and protect the rare birds were established in the middle of the 1990s. In spite of these new regulations, in less than 10 years, the red-crowned cranes lost nearly 60% of their natural habitat (Zuo et al., 2004). In 2001, the total area of the Yancheng Biosphere Reserve was 4533 km^2, with a 138 km^2 core area kept in its natural state, a 478 km^2 buffer zone used for tourism, public education and research activities, and a 3948 km^2 transitional zone containing various kinds of economic activities. In this study, the reserve area was divided into six subsystems designated by Roman numerals. The subsystems are farmland (I), aquaculture ponds (II), freshwater marsh (III), salt marsh (IV), saltpans (V) and mud flat (VI) and were defined based on information in past studies (Li, 2000; Qin et al., 2000; Liu and Luan, 2000; Dong et al., 2005; Li et al., 2004). Agriculture, aquaculture, reed harvesting and salt production are important economic activities within the reserve.

The Maipo Nature Reserve (22°30′N, 114°00′E) is located in Hong Kong harbor, a subtropical area with high biodiversity. In this 380 ha area, the main vegetation types are mangroves and bulrushes, which have a high Net Primary Production (NPP). The Maipo reserve obtained economic benefits from the services and facilities associated with fishing (Qin et al., 2000). The *S. alterniflora* ecological engineering system (33°70′N, 120°20′E) was established for dike protection in Sheyang county and every year, after the typhoon season, the above ground biomass is harvested to make a mineral supplement for human consumption (Liu et al., 2004). It has natural environments similar to those in the Yancheng reserve within a 150 ha area.

3. Methods

The emergy evaluation of the Yancheng reserve was performed following the standard guidelines (Odum, 1996). First, the system and subsystem boundaries, important external sources of emergy, principal system components, and energy and material flows were listed and then they were expressed as a diagram using the Energy Systems Language (Odum, 1994). Next, historical data on rainfall, solar radiation, wind, hydrology, biodiversity, biomass, and Net Primary Production (NPP), along with money flows and other necessary information were collected and used to calculate energy and material flows using the standard formulas (Odum, 1996; Campbell et al., 2005). Following this, emergy analysis tables were set up, and the emergies of the environmental, biological and economic aspects of the system were calculated using the following equations for determining emergy (Odum, 1996).

$$\text{Solar emergy(sej)} = \text{Solar transformity (sej/J)} \times \text{available energy (J)} \qquad (1)$$

$$\text{Solar emergy (sej)} = \text{Specific solar emergy (sej/g)} \times \text{mass (g)} \qquad (2)$$

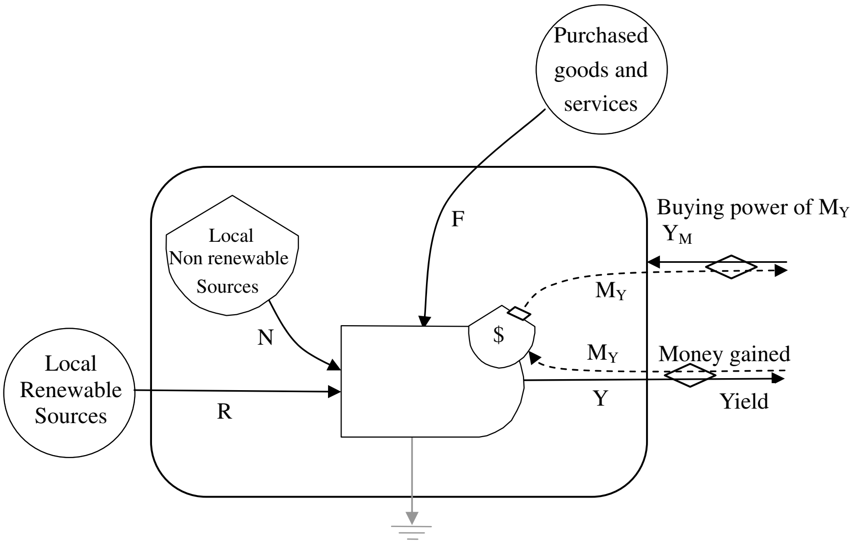
$$\text{Solar emergy (sej)} = \text{Emergy/\$} \times \text{money (\$)} \qquad (3)$$

Transformity is the factor by which available energy is multiplied to obtain emergy. It is a measure of the position of any component or flow within its hierarchy. When transformities for similar products are compared the lower transformity indicates the more efficient production process. The structure and interrelationships of natural resources and socioeconomic activities were made clear through making and evaluating the Energy Systems Diagram.

Odum (1996, p. 83) presents a standard diagram for analyzing the ecological-economic interface. The diagram analyzes the interface and its characteristics through development of a suite of indices, i.e., the emergy yield ratio (EYR, Odum, 1996), the environmental loading ratio (ELR, Odum, 1996), emergy sustainability index (ESI, Brown and Ulgiati, 1997). Fig. 2 is a modification of this diagram to allow definition of these standard indices and to define indices that capture the effects of market exchange on the system. The EYR is used primarily to show the effectiveness of the emergy purchased or invested in producing a yield. The ELR estimates the intensity of the environmental loading that results from obtaining a certain yield, whereas, the ESI compares the yield to the loading to determine if the activity is sustainable, i.e., high yields and low loading make the activity more sustainable. The effect of market exchange on the emergy balance of a system is considered through the emergy exchange ratio (EER, Odum, 1996) which is the ratio of the emergy purchasing power (Y_M) of the money received (M_Y) for the yield to the emergy of the yield (Y). A similar modification for EYR is EYR′, which shows the emergy benefit gained by the seller of an economic product for each unit of emergy invested in its production. Activities with the highest EYR′ should result in the greatest benefits to the production system. This principle was applied to sustainability by defining the emergy index of sustainable development (EISD), which takes into account the effects of market exchange and looks at what is sustainable from the standpoint of the production system (Lu et al., 2002b).

3.1. *Overall structure of the analysis*

The structure of emergy flow in the wetland reserve (Fig. 3) was analyzed by separating the ecological flows into renewable (R) and nonrenewable (N) resources and the storages into the ecological and economic components, e.g., the various plant groups, animal groups, mud, peat, and conservation infrastructure. The nonrenewable resources are further divided into renewable resources used in a nonrenewable manner (N_0), e.g. ground water pumped faster than it is recharged, and nonrenewable resources per se (N), such as peat or coal. Changes in renewable and nonrenewable natural capital storages within the reserve were indicated by ΔQ, which is the sum of changes in peaty sediment (ΔP), organic matter in the mud (ΔOM) and plant biomass (ΔB). Primary producers (B) and benthic fauna (Z_1) were compared among the different



Emergy Yield Ratio (EYR) =Y/F

Environmental Loading Ratio (ELR) = (N+F)/R

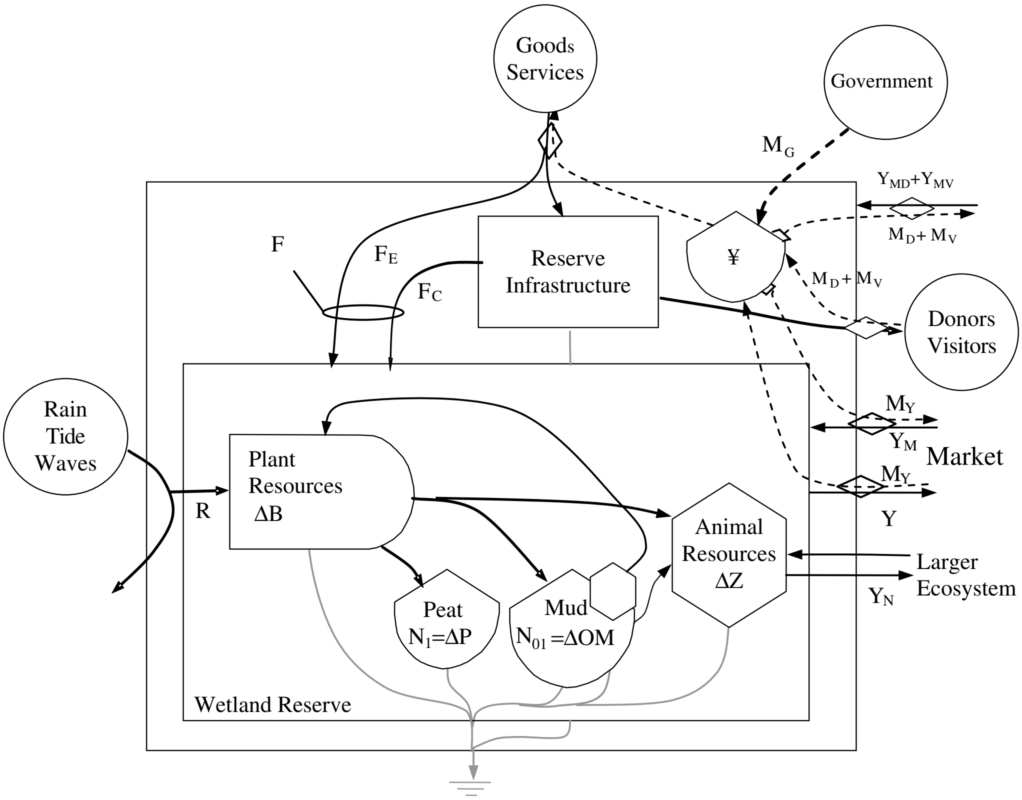
Emergy Sustainability Index (ESI) = EYR/ELR

Emergy Exchange Ratio (EER) = Y_M/Y, where $Y_M = M_Y \times$ Emergy/$ of the larger system

Emergy Yield Ratio after exchange (EYR′) = EYR×EER = Y_M/F

Emergy Index of Sustainable Development (EISD) = EYR′/ELR = EYR×EER/ELR

Fig. 2 – An energy systems diagram of a system at the ecological-economic interface modified from Odum (1996) that gives the definition of the standard emergy indices, which describe the interaction of local renewable and nonrenewable sources and purchased goods and services to make products for market exchange.



Conservation Value (CV) = $\Delta Q+Y_N = \Delta P+\Delta B+\Delta OM+Y_N$

Social Self-Sufficiency Ratio (SSR) = $(Y_M+Y_{MD}+Y_{MV})/F = (M_Y+M_D+M_V)(\text{Em}/\$)/(F_C+F_E)$

Emergy Conservation Ratio (ECR) = CV/F_C

Emergy Benefit Ratio (EBR) = $(CV+Y)/F$

Emergy Benefit in Exchange (EBE) = $(CV+Y_M+Y_{MD}+Y_{MV})/(CV+Y)$

Emergy Index of Sustainable Development (EISD) = EBR × EBE/ELR

M_Y -- the money received for economic services and products;
M_D -- the money contributed by private donors for conservation;
M_V -- the entrance fees paid by visitors;
Y_{MD} -- the emergy purchased with money contributed by private donors;
Y_{MV} -- the emergy purchased with money from visitors;
Y_{MG} -- the emergy purchased with the money contributed by government to support the reserve;
F_C -- the emergy purchased to support conservation, which is equal to $Y_{MD}+Y_{MV}+Y_{MG}$;
F_E -- the emergy purchased to support economic production.

Fig. 3 – Emergy systems diagram used to define conservation value, social self-sufficiency ratio, and to show the formulations for the revision of emergy conservation ratio, emergy benefit ratio, emergy benefit in exchange and emergy index of sustainable development (Lu et al., 2006) to include conservation value.

subsystems to examine different efficiencies of resource use and the ratio between prey (Z_1) and consumers (Z_2) was used to evaluate the carrying capacity for upper trophic level species, i.e. waterfowl, wading birds, etc. Natural products, e.g., birds and fish, supported for part of the year in the reserve before moving on were designated by Y_N. We used the rules of emergy algebra (Odum, 1996) to determine the emergy required for any flow within the Yancheng reserve system.

For the purpose of evaluating the conservation value of the reserve and comparing it to other locations we assumed that the plant biomass is in an approximate steady state. Of course, this is not strictly true with regard to the mud flat and *Spartina* subsystems, because deposition and erosion of mud and marsh growth and decline are active along the Jiangsu coast driven by larger scale geological processes.

3.2. *Structure of the economic analysis*

Based on past socioeconomic investigations (Wang et al., 2001; Lu et al., 2002a; Bai, 2006), data on the expenditures of government, donors, and visitors were converted to emergy through multiplication by the emergy/$ ratio for China in

2000 (Shen, 2001). This allowed an integrated evaluation of natural resources and socioeconomic actions. Economic production activities were evaluated separately for comparison with conservation uses and to develop strategies for optimization of the entire system. Economic production was evaluated based on relative differences in empower density, emergy yield ratio (EYR), the emergy yield ratio after market exchange (EYR′), and the emergy exchange ratio (EER). Empower density shows the intensity of emergy use on the landscape and it is generally greater for more developed areas.

3.3. *Emergy base for the subsystems*

The wind, rain, and waves are co-products coming from solar energy (Odum, 1996). For many terrestrial systems the maximum emergy input is contained in the chemical potential energy of rain (Table 1). Inputs that are co-products of the same planetary processes need to be handled in a manner that avoids double counting. The general rule to avoid double counting is to only count the largest input from the same source for any given area, but this method can be modified in special cases (Odum et al., 1987). The tidal contribution to the global transformities of rain, river water, and waves was removed so that tide, rain, and river water could be counted in the emergy base for the *Spartina* marsh subsystem, thereby giving a more accurate estimate of the degree to which planetary emergy has been concentrated in this coastal area. A similar adjustment of waves, tides and river water constituted the emergy base for the productivity of the mud flat subsystem.

4. Results

The results of this research are divided into four categories and presented in this section. First we consider the development and revision of emergy indices to include an expression that begins to capture the conservation value of lands held in nature reserves in a manner that is comparable to the products of economic uses for the same land. Next we consider the results of an evaluation of the structure of natural resources in the Yancheng reserve. This is followed by presentation of the results of analyzing the economic production systems in the transitional zone. Finally, we consider conservation activities within the reserve and how the Yancheng Biosphere Reserve compares to the Maipo Nature Reserve and a *Spartina* ecological-engineering system.

4.1. *Definition of new quantities and indices and the expansion of existing indices*

Commonly-used emergy indices do not include several factors that are important in documenting the ecological benefits of conservation, specifically, the accumulation of renewable and nonrenewable resources inside the system and the support that the system provides for larger ecosystems. This is understandable since most emergy indices have been developed to capture the use and effects of natural and purchased resources in obtaining economic products and/or in providing support for society. The methodological problem faced in this study was to develop emergy indices suitable for evaluating conservation activities and decisions when both the ecological and economic benefits of natural lands must be considered on an equal basis.

This paper takes a systematic approach to defining the value added by nature reserves, parks and other environmental assets of society. In this approach we modified the standard energy systems diagram of the ecological economic interface by adding the components that were needed to describe the growth of renewable and nonrenewable natural capital within the reserve and the provision of natural products to larger ecological systems. These modifications allowed us to define a new quantity, Conservation Value (CV). In addition, the Social Self-Sufficiency Ratio (SSR) was defined to demonstrate the degree to which a system is supported by the economic revenues generated through its use. The new quantity and index and the expansion of four exiting indices to include CV are defined by referring to Fig. 3.

In a preceding study, Zuo et al. (2004) used emergy to evaluate the sustainability of the original Yancheng wetlands (not including *Spartina*), a pond constructed to support waterfowl, and an aquaculture pond. The value of land used for conservation purposes is an implicit problem in their analysis, but it was not addressed directly. They proposed that the emergy potentially re-circulating in the system or the base emergy change (BEC) was a measure of the emergy stored in the system and an indicator of sustainability. The relationship of flows to system storages is not clear 'a priori' and it is the maximization of emergy flow not storage that determines the competitiveness of systems (Odum, 2007). Despite several technical problems in the calculation of their ecological indicators, the overall results of the analysis are plausible, and perhaps, indicative of the robustness of emergy indices in general.

The Social Self-Sufficiency Ratio (SSR) is equal to the emergy resources supplied from the private sector divided by total emergy purchased from the socioeconomic system. The emergy input that can be purchased with the various monetary inflows is calculated by multiplying the monetary flow by the emergy to money ratio. If the SSR is equal to or greater than 1, the reserve system is sustainable using only the emergy supplied from the private sector. Zuo et al. (2004) proposed an index of economic benefit or Net profit (Np), which is the difference between the emergy of economic income and the purchased emergy required to maintain the system. This index has a similar purpose with the SSR, but it uses a difference rather than a ratio, thus, when the Np is negative, the SSR will be less than 1.

The Emergy Conservation Ratio (ECR) expands the idea of the Ecological Restoration Ratio (ERR), which included changes in renewable natural capital, within the system as part of the benefit gained from restoration (Lu et al., 2006). The ECR changes this index to include the additional aspects of conservation value. It is equal to the change in the emergy value of all natural renewable and nonrenewable stored resources of the system plus the annual support given to larger

Table 1 – Emergy accounting table for Yancheng Biosphere Reserve

Note	Item	Raw data	Units	Solar emergy per unit	Solar emergy (sej/y)
I. Farm land					
1	Solar radiation	1.00E+18	J	1[a]	1.00E+18
2	Wind velocity	1.29E+16	J	1470[b]	1.90E+19
3	Earth heat flux	6.79E+14	J	33,700[b]	2.29E+19
4	Rain, geopotential	5.77E+12	J	10,300[b]	5.94E+16
5	Rain, chemical potential energy (Ia)	1.39E+15	J	18,100[b]	2.52E+19
6	River inflow, chemical potential	2.17E+16	J	50,100[b]	1.09E+21
7	River water used for irrigation (Ib)	8.35E+14	J	50,100[b]	4.18E+19
8	Purchased inputs (Ic)				4.16E+20
9	Rice harvested	1.82E+15	J	2.65E+05[c]	4.83E+20
10	Rice left in field	7.12E+11	J	2.65E+05[c]	1.89E+17
11	River outflow, chemical potential	2.09E+16	J	50,100[b]	1.05E+21
II. Aquaculture ponds					
1	Solar radiation	8.75E+17	J	1[a]	8.75E+17
2	Wind velocity	5.64E+15	J	1470[b]	8.29E+18
3	Earth heat flux	5.94E+14		33,700[b]	2.00E+19
4	Rain, geopotential	5.04E+12	J	10,300[b]	5.19E+16
5	Rain, chemical potential energy (IIa)	1.21E+15	J	18,100[b]	2.20E+19
6	River inflow, chemical potential	2.09E+16	J	50,100[b]	1.05E+21
7	River water used for aquaculture, (IIb)	5.39E+15	J	50,100[b]	2.70E+20
8	Phytoplankton (IIa + IIb)	2.79E+16	J	1.04E+04[c]	2.92E+20
9	N fertilizer	7.53E+08	g	3.73E+09[a]	2.81E+18
10	P fertilizer	1.13E+09	g	3.83E+09[a]	4.33E+18
11	Forage	1.76E+11	g	1.31E+09[d]	2.30E+20
12	Fry	1.60E+10	g	1.45E+10[d]	2.31E+20
13	Other purchased input				6.85E+19
	Total of purchased inputs (IIc)				5.37E+20
14	Aquaculture output, a split	3.02E+14	J	1.71E+06[c]	5.16E+20
15	Benthic fauna left in pond, a split	1.83E+14	J	1.71E+06[c]	3.13E+20
16	OM increase in mud[e]	8.93E+14	J	9.28E+05[c]	8.29E+20
17	River outflow, chemical potential	1.55E+16	J	50,100[b]	7.77E+20
III. Pharagmites and Aeluropus					
1	Solar radiation	8.61E+17	J	1[a]	8.61E+17
2	Wind velocity	1.11E+16	J	1470[b]	1.63E+19
3	Earth heat flux	5.84E+14		33,700[b]	1.97E+19
4	Rain, geopotential	4.96E+12	J	10,300[b]	5.11E+16
5	Rain, chemical potential energy	1.20E+15	J	18,100[b]	2.16E+19
6	River inflow, chemical potential	1.55E+16	J	50,100[b]	7.77E+20
7	Evapotranspiration[f]	1.78E+15	J	4.78E+04[c]	8.49E+19
	from rain (IIIa$_1$)	1.27E+14	J	18,100[b]	2.30E+18
	from river water (IIIb$_1$)	1.69E+15	J	50,100[b]	8.26E+19
8	Water stored in peaty sediment[f]	2.61E+13	J	4.79E+04[c]	1.25E+18
	from rain (IIIa$_2$)	1.76E+12	J	18,100[b]	3.19E+16
	from river water (IIIb$_2$)	2.43E+13	J	50,100[b]	1.22E+18
9	Purchased input for harvest of *Pharagmites* (IIIc$_1$)	2.41E+05	$ in 2001	4.94E+12[d]	1.19E+18
10	NPP of *Pharagmites* and *Aeluropus* (IIIa1 + IIIb$_1$)[f]	1.06E+16	J	8.00E+03[c]	8.49E+19
	Pharagmites harvested	3.35E+14	J	1.15E+04[c]	3.87E+18
	NPP left after harvest	1.03E+16	J	8.00E+03[c]	8.22E+19
11	Peaty sediment (IIIa1 + IIIb$_1$ + IIIa2 + IIIb$_2$)[g]	3.78E+15	J	2.28E+04[c]	8.61E+19
12	Annual production of benthic fauna (IIIa1 + IIIb$_1$)	3.52E+14	J	2.41E+05[c]	8.49E+19
13	River outflow, chemical potential	1.38E+16	J	50,100[b]	6.93E+20
14	Rain infiltration	1.07E+15	J	18,100[b]	1.93E+19
IV. Spartina and Suaeda					
1	Solar radiation	1.80E+18	J	1[a]	1.80E+18
2	Wind velocity	2.32E+16	J	1470[b]	3.42E+19
3	Earth heat flux	1.22E+15	J	33,700[b]	4.12E+19
4	Rain, geopotential	1.04E+13	J	10,300[b]	1.07E+17
5	Rain, chemical	2.50E+15	J	18,100[b]	4.53E+19
6	River inflow, chemical potential	1.38E+16	J	50,100[b]	6.93E+20
7	Evapotranspiration	1.85E+15	J	3.91E+04[c]	7.23E+19
	From rain (IVa$_1$)	2.83E+14	J	15,600[b,h]	4.42E+18
	From river water (IVb$_1$)	1.57E+15	J	43,300[b,h]	6.79E+19

(continued on next page)

Table 1 – continued

Note	Item	Raw data	Units	Solar emergy per unit	Solar emergy (sej/y)
8	Water stored in peaty sediment[f]	5.47E+13	J	3.91E+04[c]	2.14E+18
	from rain (IVa$_2$)	8.25E+12	J	15,600[b,h]	1.29E+17
	from river water (IVb$_2$)	4.65E+13	J	43,300[b,h]	2.01E+18
9	Tide (IVd)	5.31E+15	J	24,300[b]	1.29E+20
10	NPP of *Spartina* and *Suaeda* (IVa1 + IVb$_1$ + IVd)	1.34E+16	J	1.50E+04[c]	2.01E+20
11	Peaty sediment (IVa1 + IVb$_1$ + IVa2 + IVb2 + IVd)	1.40E+16	J	1.45E+04[c]	2.03E+20
12	Annual production of benthic fauna (IVa1 + IVb$_1$ + IVd)	7.36E+14	J	2.73E+05[c]	2.01E+20
13	River outflow, chemical potential	1.22E+16	J	50,100[c]	6.12E+20
14	Rain infiltration	2.21E+15	J	18,100[c]	4.00E+19
V. Saltpans					
1	Solar radiation	1.13E+18	J	1[1]	1.13E+18
2	Wind velocity	7.30E+15	J	1470[2]	1.07E+19
3	Earth heat flux	7.69E+14	J	33,700[2]	2.59E+19
3	Rain, geopotential	6.53E+12	J	10,300[2]	6.73E+16
4	Rain as materials (Va)	3.33E+14	g	84,954[i]	2.83E+19
5	Seawater (Vh)	5.38E+07	m^3	1.84E+10[j]	9.90E+17
6	Evaporation, (Va + Vh)	2.43E+15	J	1.21E+04[3]	2.93E+19
7	Fuels and goods (Vc$_1$)[k]				4.77E+19
8	Labor and services (Vc$_2$)	2.09E+13[8]	J	1.70E+06[l]	3.56E+19
	Subtotal of purchased input for salt production (Vc)				8.33E+19
9	Salt output (Va + Vh + Vc)	9.36E+11	g	1.20E+08[c]	1.13E+20
10	Annual production of benthic fauna (Va +Vh + Vc)	2.95E+14	J	3.81E+05	1.13E+20
VI. Mud flat					
1	Solar radiation	7.19E+18	J	1[a]	7.19E+18
2	Wind velocity	4.64E+16	J	1470[b]	6.82E+19
3	Earth heat flux	4.88E+15	J	33,700[b]	1.64E+20
4	Rain, geopotential	4.14E+13	J	10,300[b]	4.27E+17
5	Rain, chemical	9.98E+15	J	15,600[b,h]	1.56E+20
6	River inflow, chemical potential (VIb)	7.71E+15	J	43,300[b,h]	3.34E+20
7	wave (VIe)	5.99E+16	J	25,900[a,h]	1.55E+21
8	Tide (VId)	2.12E+16	J	24,300[b]	5.14E+20
9	NPP of phytoplankton (VIb + VIe + VId)	2.30E+17	J	1.04E+04[c]	2.40E+21
10	Annual production of benthic fauna (VIb + VIe + VId)	2.84E+15	J	8.39E+05[c]	2.40E+21
Waterfowl					
1	Artificial forage (mainly corn)	9.87E+10	J	63,000[b]	6.22E+15
2	Waterfowls, (rice + forage + benthic fauna)	1.02E+13	J	5.12E+07[cc]	5.22E+20
Yancheng Biosphere Reserve					
	Environmental Resources used, *R*				3.08E+21[m]
	Purchased input for economic production, F_E				1.04E+21[n]
	Harvest, Y_E				1.11E+21[o]
	Conservation input, Fc[6]	8.89E+07	US$2000	4.94E+12[d]	4.39E+20
	Donors' and visitors' contribution				9.52E+18
	Government				4.38E+20
	Plant resources in reserve, *B*[p]	2.81E+17	J	1.06E+04	3.00E+21
	Increase in pond mud, ΔOM	8.93E+14	J	9.28E+05	8.29E+20
	Peaty sediment, Δ*P*	1.17E+16	J	2.48E+04	2.89E+20
	Benthic Fauna not eaten by birds, ΔZ_1	3.42E+15	J	7.57E+05	2.59E+21
	Waterfowl biomass supported, ΔZ_2	1.02E+13	J	5.12E+07	5.22E+20
	Storage change of Yancheng reserve (ΔOM + Δ*B* + Δ*P*)				1.12E+21
	Support for fauna in larger natural systems ($\Delta Z_1 + \Delta Z_2$)[q]				3.11E+21

All transformities and specific emergies are relative to the 9.26E+24 sej/y planetary baseline (Campbell, 2000).

a Odum (1996), adjusted to the 9.26 baseline except solar which is one for all baselines.

b Campbell et al. (2005) and Campbell (2000) for tide.

c This study.

d Shen (2001).

e Assume OM increase is a co-product with the plant and ultimately the animal resources of the ponds.

f Sub-items below included.

g Assume peaty sediment to be a co-product with plant NPP.

h Transformities of river and rain water transpired and waves are adjusted to avoid double counting with tide.

i Odum (2000), transferred the emergy baseline from 15.83E+24 sej/y to 9.26E+24 sej/y

j Based hydrologic cycle data from: http://hypertextbook.com/facts/2001/SyedQadri.shtml and http://webworld.unesco.org/water/ihp/db/shiklomanov/summary/html/summary.html (Summary of the monograph "World Water Resources At the Beginning Of the 21st Century"

Table 1 – continued

prepared in the framework of IHP UNESCO). Replacement time of the world oceans using evaporation is 2860 y × 9.26E+24 sej/y = 2.48E+28 sej emergy required to form seawater in the present world oceans. Mass of world oceans 1.38E+24 g and the specific emergy of sea water is 1.8E+4 sej/g. Volume of world oceans is 1.347E+18 m^3 and the emergy per m^3 is 1.84E+10 sej m^{-3}.

k Babic (2005).

l Lan and Odum (1994).

m R = River water used + rain chemical potential used on farmland, aquaculture ponds, and the two marsh subsystems + rainwater and seawater as material inputs to saltpans + tide on both salt marsh and mudflat + waves on the mudflat.

n F_E = purchased input for agriculture, aquaculture, reed cutting and salt production.

o Y_E = total emergy as products harvested, including rice, aquaculture products, part of the NPP of reeds, and salt.

p Assume that plant production is in steady-state, and that all of the plant biomass left after harvest was used to support the animals, so that the annual ΔB was 0.

q Assume all of the birds and fish migrate out of the reserve during part of the year.

ecosystems through the export of emergy in natural products and services divided by the emergy purchased from the economy for conservation (Fig. 3).

The Emergy Benefit Ratio (EBR) considers both the increase in economic production and the change in Conservation Value (CV) compared to the total emergy purchased from the economy (Fig. 3). Emergy Benefit in Exchange (EBE) is the ratio of the conservation value plus emergy purchasing power of the money received from donors, visitors, and products sold on the market to CV plus the emergy of the products sold. The EBE shows the effect of market exchange on the emergy balance of the local system (Fig. 3). The expression for the

Table 2 – Annual economic flows in the Yancheng Biosphere Reserve

Note	Item	Raw data[a] ($ unless noted)	Emergy/money[b] (sej/$)	Solar emergy (sej)/y	Percent $ (%)
Conservation activities					
	Infrastructure for Management	8.82E+07	4.94E+12	4.36E+20	99.30
	Infrastructure for Education and Research				
1.	Research	7.31E+04	4.94E+12	3.61E+17	0.08
2.	Education and ecological tourism	5.48E+05	4.94E+12	2.71E+18	0.62
	Subtotal		3.07E+18	0.70	
Total expenditure for conservation (F_C)			4.39E+20	100	
Empower density of conservation, F_C (m^2)			9.68E+10		
EYR for conservation expenditures, Y_N/F_C			7.09		
	Financial income				
1.	Government budget			4.29E+20	97.83
2.	Donors and visitors' contribution ($M_D + M_v$)	4.67E+05	4.94E+12	9.52E+18	2.17
	Ticket income (M_v)	6.02E+04	4.94E+12	2.98E+17	0.07
Private economic activities					
1	Emergy buying power received for rice, Y_{M1}	4.41E+07	4.94E+12	2.18E+20	
	Empower density of rice culture, F_{E1} (m^2)			1.45E+12	
	EYR of rice production			1.16	
	EER of rice output			0.45	
	EYR′ = Y_{M1}/F_{E1}			0.52	
2	Emergy buying power received for aquaculture products,Y_{M2}	6.28E+07	4.94E+12	3.10E+20	
	Empower density of aquaculture culture, F_{E2} (m^2)			2.14E+12	
	EYR of aquaculture production			0.96	
	EER of aquaculture output			0.60	
	EYR′ = Y_{M2}/F_{E2}			0.58	
3	Emergy buying power received for reed, Y_{M3}	8.67E+05	4.94E+12	4.29E+18	
	Empower density of reed harvesting, F_{E3} (m^2)			1.11E+10	
	EYR of reed harvesting			3.25	
	EER of reed output			0.85	
	EYR′ = Y_{M2}/F_{E3}			3.60	
4	Emergy buying power received for salt output, Y_{M4}	2.26E+08	4.94E+12	1.11E+21	
	Empower density of salt production, F_{E4} (m^2)			2.56E+11	
	EYR of salt production			1.35	
	EER of salt output			9.90	
	EYR′ = Y_{M4}/F_{E4}			13.39	

a Original data in RMB converted to US $ in 2000 by multiplying by 8.3.

b Shen, 2001 (emergy/$ in China, 2000).

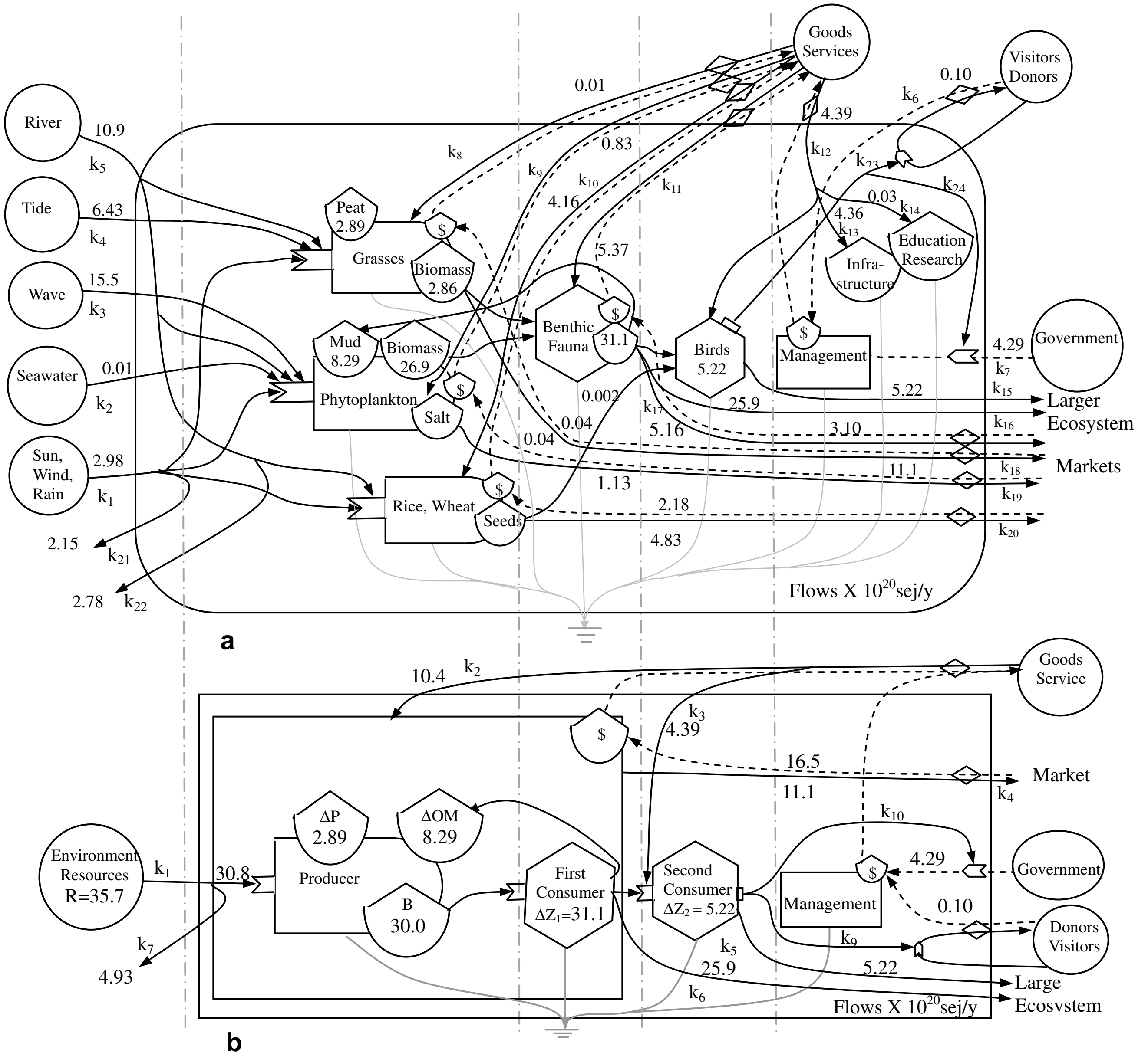


Fig. 4 – An energy systems model of the Yancheng Biosphere Reserve showing emergy inflows, outflows, and changes in system storages: (a) the detailed model of the system and (b) a simplified version of the model.

Emergy Index of Sustainable Development (EISD) including CV is the same as originally defined but using the modified indices (Fig. 3, Lu et al., 2002b).

4.2. *Value and structure of natural resources*

The inputs and key elements of the reserve system and its subsystems (I-VI) are given in Table 1. The calculations, references, and assumptions needed to obtain the energy and emergy values for the external forcing functions, internal components, and pathway flows (Table 1) are given in the Appendix.

The annual economic flows are shown in Table 2 along with the supporting data sources and assumptions. The transformities of several biological components and flows were calculated in this study (italics in Table 1). From Table 1, we can determine the emergy basis for productivity in each of the subsystems (I–VI). The emergy flows shown in Table 1 were aggregated in Fig. 4 by combining functionally similar energy inflows and outflows, which were defined in Table 3. The aggregated diagram facilitated the calculation of indices (Table 4) for the evaluation of economic and conservation actions.

The total emergy used in the reserve was 4.55E+21 sej/y with 67.6% coming from renewable environmental resources, 22.8% from purchased input for economic production and 9.6% from purchased inputs for conservation. The largest input of renewable environmental resources

Table 3 – Definition of the emergy flows on the energy systems diagrams in Fig. 4a and b

Item	Emergy $\times 10^{20}$ sej/y	Definition
Fig. 4a		
k_1	2.98	Chemical potential energy of rain water
k_2	0.01	Seawater evaporated in saltpans
k_3	15.5	Wave energy absorbed by mudflat
k_4	6.43	Tide energy absorbed by *Spartina* and *Suaeda* and mudflat
k_5	10.9	Chemical potential energy of river water inflows
k_6	0.10	Emergy buying power of the money from donors and visitors
k_7	4.29	Emergy buying power of the money from government
k_8	0.01	Services used for reed harvesting
k_9	0.83	Goods and services used for salt production
k_{10}	4.16	Goods and services used for farming
k_{11}	5.37	Goods and services used for aquaculture production
k_{12}	4.39	Goods and service used for conservation management
k_{13}	4.36	Goods and services used on infrastructure for management
k_{14}	0.03	Goods and services used on research and education
k_{15}	5.22	Birds emigrating to the larger ecosystem
k_{16}	25.9	Fish emigrating to the larger ecosystem
k_{17}	5.16	Aquaculture products (fish, shrimp, etc.) harvested
k_{18}	11.1	Reeds harvested
k_{19}	1.13	Salt yield
k_{20}	4.83	Rice harvested
k_{21}	2.15	Chemical potential energy of rain water infiltrating the ground
k_{22}	2.78	Chemical potential energy of river water entering East China Sea
k_{23}	5.22	Birds supported attracting investment from donors and visitors
k_{24}	5.22	Birds supported attracting investment from government
Fig. 4b		
k_1	35.7	Inflow of all renewable natural resources
k_2	10.4	Purchased input for economic production
k_3	4.39	Purchased input for conservation management
k_4	11.1	Economic products output to market
k_5	5.22	Birds emigrating to larger ecosystem
k_6	25.9	Fish emigrating to larger ecosystem
k_7	4.93	Unused renewable natural resources flowing out of the system
k_8	5.22	Birds supported attracting investment from donors and visitors
k_9	5.22	Birds supported attracting investment from government

was from wave energy (1.55E+21 sej/y). River water is the second largest renewable environmental input, 1.09E+21 sej/y. Of this amount about 75% is used within the reserve boundaries to support ecological processes. Tides are the third largest natural emergy input to the reserve (6.43E+20 sej/y) and are absorbed in the salt marsh and mud flat.

The change in emergy stored in the marsh subsystems is equal to the sum of the emergy basis for peaty sediment deposition, 2.89E+20 sej/y (Table 1, Fig. 4), whereas, the maximum support from the marshes to larger natural systems is the emergy of the benthic fauna, 2.86E+20 sej/y (Table 1, Fig. 4). The total change of the emergy of natural capital in the Yancheng reserve, 1.12E+21 sej/y (Tables 1 and 3), is the sum of the change in the storages within the subsystems. The support given to larger ecosystems by bird and fish migrations contributes 3.11E+21 sej/y (Table 3, Fig. 4).

The reserve supplied 1.11E+21 sej/y of economic products (rice, reeds, fish, and salt), and used 1.04E+21 sej/y of purchased inputs in the production process (Fig. 4). Society received 4.83E+20 sej/y of benefit from the agricultural subsystem for 4.16E+20 sej/y of purchased input. Current aquaculture operations are not yielding the optimum benefit to society, because only 62.2% of the fish and benthic fauna raised in the ponds were harvested. The transformity of pond benthic fauna was 7.08 times greater than that under the common reed and *Aeluropus littoralis* (Gouan) indicating the relative inefficiency of benthic production in the ponds. Similarly, the transformity of benthic fauna on barren mudflat was 3.09 times that found in the *Spartina* and *Suaeda* subsystem.

4.3. *Evaluation of economic activities*

The total investment in management and education-research in the Yancheng Biosphere Reserve was 4.39E+20 sej/y (Table 2). Of this amount less than 1% was spent on education, tourism, and research and only 12% of this was used for academic research. Also, the emergy purchased with the money contributed by donors and visitors was only 2.2% of the total investment needed to support conservation, whereas, the remaining 97.8% was supplied by government.

Table 4 – Emergy evaluation indices for the Yancheng Reserve, Maipo Reserve and Sheyang S. alterniflora ecological engineering system

Flow and indices	Expression/function	Yancheng Reserve	Maipo Reserve[a]	*S. alterniflora* Eco-engineering[b]
Renewable environmental resources input	R	3.08E+21	1.51E+18	2.42E+17
Nonrenewable environmental resources input	N	0	0	0
Purchased input	$F = F_C + F_E$	1.48E+21	4.18E+17	2.38E+18
Total input	$U = R + N + F$	4.55E+21	1.93E+18	2.62E+18
Storage exchange				
Peaty sediment	ΔP	2.89E+20	5.69E+17	1.97E+18
Mud	ΔOM	8.29E+20		
Plant resources	ΔB		3.48E+17	
Change in storage of natural capital	$\Delta Q = \Delta P + \Delta OM + \Delta B$	1.12E+21	9.16E+17	1.97E+18
Support for large natural systems, Y_N				
Animal resources supported	$Y_N = \Delta Z_1 + \Delta Z_2$	3.11E+21	1.08E+18	
Conservation value	$CV = \Delta Q + Y_N$	4.23E+21	1.43E+18	
Economic yield	Y	1.11E+21	1.61E+18	1.97E+18
Donors' and visitors' contributions	$Y_{MD} + Y_{MV}$	9.52E+18	2.49E+17	
Market reward (emergy)	Y_M	1.65E+21	1.61E+18	1.19E+19
Environmental loading ratio	$ELR = (F + N)/R$	0.48	0.28	14.27
Emergy yield ratio	$EYR = (Y + Y_N)/F$	2.86	6.44	0.57
Emergy sustainability index	$ESI = EYR/ELR$	5.96	23.24	0.04
Social self-sufficiency ratio	$SSR = (Y_{MD} + Y_{MV} + Y_M)/F$	1.12	4.45	3.43
Emergy conservation ratio	$ECR = CV/F_C$	9.63	3.42	0.57
Emergy benefit ratio including conservation value	$EBR = (CV + Y)/F$	3.62	7.27	1.14
Emergy benefit in exchange including conservation value	$EBE = (CV + Y_{MD} + Y_{MV} + Y_M)/(CV + Y)$	1.10	1.08	3.51
Emergy index of sustainable development	$EISD = (EBR \times EBE)/ELR$	8.30	28.39	0.28

a Qin et al. (2000): We changed the emergy baseline from 8.0E24 sej/y to 9.26E24 sej/y.

b Liu et al. (2004): We changed the emergy baseline from 8.0E24 sej/y to 9.26E24 sej/y.

The empower density (sej m^{-2}) of investments in agriculture and aquaculture was, respectively, 15 and 22 times higher than that for conservation (Table 2). The empower density of economic activities in the reserve increased from a minimum of 1.11E+10 sej m^{-2} for reed harvesting, through salt production (2.56E+11) and rice culture (1.45E+12) to a maximum of 2.14E+12 for aquaculture ponds (Table 2). The Emergy Yield Ratio follows an opposite trend from a maximum of 3.25 for reed harvesting to a minimum of 0.96 for aquaculture ponds (Table 2). The emergy yield ratio (EYR) of conservation (7.09) was 2.18, 5.25, 6.11 and 7.39 times that of reed harvesting, salt production, rice planting and aquaculture production, respectively. Salt production had the highest (13.39) EYR′, Emergy Yield Ratio after market exchange, followed by reed harvesting (3.60) and then aquaculture (0.58) and finally rice culture (0.52). Comparing the two most intense land uses (Table 2), aquaculture ponds have a higher Emergy Exchange Ratio (EER), empower density and EYR′, than rice culture.

4.4. *Evaluation and comparison of conservation and ecological-engineering activities*

A suite of emergy indices was calculated for ecological-economic evaluation of the reserve, and to compare the Yancheng indices with similar indices calculated for the Maipo Nature Reserve and the *S. alterniflora* ecological-engineering system (Table 4). The magnitude of Conservation Value (CV) in the Yancheng reserve was 3000 times greater than the CV of the Maipo reserve, reflecting the difference in area of the two systems. The Emergy Conservation Ratio (ECR) of Yancheng reserve was 2.83 times that of the Maipo reserve, showing the relative return on investments in conservation at the two sites. The Environmental Loading Ratio (ELR) of the Yancheng reserve was 1.71 times that of the Maipo reserve, but only 0.034 of the *S. alterniflora* ecological-engineering system reflecting the density of economic activities in each place. The emergy yield ratio (EYR) of Yancheng reserve was 0.44 that of the Maipo reserve and 5.02 times the EYR of the *S. alterniflora* ecological-engineering system, reflecting the emergy return on investments from the larger system. Finally, the Emergy Sustainability Index (ESI) of Yancheng reserve was 0.26 of that in the Maipo reserve and 149 times the ESI of the *S. alterniflora* ecological-engineering system. The Emergy Index of Sustainable Development (EISD) for the Yancheng reserve was 0.29 that of the Maipo reserve and 30 times the ecological-engineering system. Thus both sustainability measures showed Maipo to be the most sustainable system, followed by Yancheng and then the ecological-engineering system.

5. Discussion

The Yancheng Biosphere Reserve is being pressured on the one hand by the rapidly expanding local economy of Yancheng city and on the other by the growing realization in China and the world that the preservation of natural lands and critical habitat is the key to preserving and protecting endangered and threatened flora and fauna. An abundant inflow of renewable environmental resources into the Yancheng reserve gives it a high capacity to support primary and secondary biological production that, in turn, provides a large store of potential energy that can be used to support conservation and/or economic production. Managers need better tools and assessment methods to best use this potential production and to accomplish their mission to preserve and increase critical habitat for rare and endangered species such as the red-crowned crane, the black-faced spoonbill (*Platalea minor*) and critically endangered Pere David's deer (*Elaphurus davidianus*), which are all found in the reserve. Conservation must become the primary goal for reserves and a secondary goal to guide the design of human-dominated areas, as proposed by Pejchar et al. (2007). The implications of the results of this study for managing nature reserves are discussed along with the benefits of incorporating emergy evaluations of conservation value in considering such important topics as the total gain or loss realized as a result of socioeconomic decisions and the ability of wetlands to sustain various human uses.

5.1. *Management of Yancheng Biosphere Reserve*

Emergy and economic measures do not always give managers the same picture of the ecological and economic benefits of alternative decisions. For example, the economic uses of reserve lands generate more revenue than conservation uses. In addition, they use more purchased inputs to match the free inputs of nature and consequently have higher empower densities. Natural areas within the reserve have a low empower density; and therefore, they are not economically competitive with agriculture and aquaculture, which attract higher investments per unit area in a free market. Using economics alone, reserve lands would probably be taken over entirely by economic uses without government intervention. In fact, this is what happened with the rapid growth of aquaculture ponds in the transitional zone in recent years (Zuo et al., 2004). In contrast, the emergy yield ratio (EYR) of conservation activities was 7.09 compared to 1.16 and 0.96 for rice culture and aquaculture, respectively. For the reserve as a whole, there is almost a 10 to 1 return on the emergy invested by government in conservation. From this perspective, society obtains a much greater yield per unit of investment in conservation compared to agriculture and aquaculture. At present, the Yancheng reserve operates mainly on government support, instead of the money gained from visitors and donors in exchange for the ecological experiences that they receive. Neither education nor research was well funded; therefore, there is an urgent need to increase ecotourism and public education at the Yancheng reserve to improve the economic benefits gained from conservation and to make people aware of the high return on investments in conservation. Whereas, ecotourism can lead to problems in some developing areas with limited resource availability (Brown and Ulgiati, 2001), this is not expected to be a problem for a rapidly developing industrial area like Yancheng.

Key problems facing the Yancheng Biosphere Reserve are how to avoid over development of aquaculture ponds on reserve lands and how to increase their efficiency and decrease the environmental impacts of those that are there already. Aquaculture ponds have a higher empower density, emergy exchange ratio (EER), and EYR′, than rice culture, and thus, aquaculture is economically more competitive. Because aquaculture was relatively inefficient, it provided some food for the waterfowl and wading birds that came to forage there. Past studies (Lu et al., 2002a), have suggested that adjusting the structure of fish species to make full use of the available habitats and forage will improve productivity and result in increased benefits. Based on Loesch et al. (2002) we estimated that 16.8% of the benthic fauna in Yancheng reserve were eaten by birds. If this estimate is accurate, current economic activities have not affected the availability of food for waterfowl and other bird populations. Several possibilities exist for using this additional productivity. Expanding the core area of the reserve (Li et al., 1999) and/or building additional ponds devoted exclusively to waterfowl and wading birds (Zuo et al., 2004) might increase bird populations throughout the reserve allowing them to use more of the available food resources. Alternatively, aquaculture optimization strategies similar to that recommended by Lu et al. (2002a) might be applied in the aquaculture ponds to use the benthic resources better.

For a long time, the price of rice was kept low by government controls to promote food security and the general welfare of the people (not necessarily the farmers). In recent years, the central government of China has paid much attention to increasing the quality of life for farmers and as a result the government has progressively increased the price of rice; thereby, increasing the Emergy Exchange Ratio (EER) and the emergy yield ratio after market exchange (EYR′) of rice culture, and the intensity of competition between rice culture and aquaculture for available land. There is some evidence from past studies (Dong et al., 2005; Ma et al., 2006) that grain fields provide preferred habitat for over-wintering red-crowned cranes; however, each year some birds are found poisoned by the pesticides used.

Reed harvesting and salt production had relatively low empower densities and as a result they have been at a disadvantage in the competition for the use of reserve lands, even though they may be more compatible with conservation than either agriculture or aquaculture. Although the economic activities in the transitional zone improved the socioeconomic viability of Yancheng reserve as a whole, the monetary gains from these economic activities were not used for conservation. Furthermore, economic activities in the reserve compete with conservation activities for land. Since the Yancheng reserve managers only have the right to determine land use in the core area, an urgent problem confronting both the Yancheng reserve and local government is how to deal with the tough competition occurring in the reserve among different land uses. Managers, not only in Yancheng reserve but also in other reserves, also face the problem of how to sustain both economic and conservation activities at optimum levels on reserve land (Cabeza and Moilanen, 2006; Bouyer et al., 2007). An analysis of the emergy indices will give some information on how this state might be achieved.

5.2. *Evaluation of the reserve systems using emergy indices*

Most conservation management problems have ecological and economic dimensions (Tisdell et al., 2005; Cumming and Spiesman, 2006; Watzold et al., 2006), and adequate solutions for such problems can be developed only if perspectives from ecology and economics are integrated (Chee, 2004; Leough and Blahna, 2006). The emergy indices calculated in this paper are integrated measures used to show various aspects of a system at the interface between environment and economy. In this paper, we defined Conservation Value (CV) to include several factors that are missing in existing emergy indices. CV is in the early stages of its development and in the future, we will expand it to include the value of biodiversity. Because biodiversity was not included, the indices presented here will give conservative estimates of the benefits of conservation.

The Social Self-Sufficiency Ratio (SSR) showed the degree to which the nature reserve could be supported on private economic activities alone and thus it gives a measure of the economic vitality of the reserve. The Maipo reserve had a higher SSR than Yancheng (Table 4), for two reasons. First, it received more support from donors and visitors (41.4% compared to 2.2% for Yancheng), and second Maipo's economic yield was from fishing which requires less emergy investment per unit of yield compared to aquaculture and farming. The *Spartina* ecological engineering system had a high SSR because it produced large economic revenues from the use of the harvested grass as a pharmaceutical mineral supplement and additional benefits were realized from a dike protecting the shoreline from erosion.

The Emergy Conservation Ratio (ECR) shows the efficacy of resources spent for conservation in producing ecological benefits. In this regard Yancheng reserve provides the most benefits for each dollar spent on conservation. This is primarily due to the support the Yancheng marshes provide for birds and fish that migrate to larger ecosystems. The Emergy Benefit Ratio (EBR) is similar to the ECR but it includes the economic as well as the ecological benefits obtained from each unit of purchased feedback from the economy. Maipo has the highest EBR followed by Yancheng primarily due to the large economic output and small investment required for the fish harvested from the mangrove reserve. The Emergy Benefit in Exchange (EBE) takes the effects of market exchange into consideration in the index, thus it includes the ecological products (Conservation Value, CV) and the emergy buying power of the money received for the economic products (Y). The shoreline protection provided by the dike, the rapid growth characteristics of *Spartina* and the high value of mineral supplements made from the plants caused the EBE of the *S. alterniflora* ecological-engineering system to be 3.18 times that of the Yancheng reserve. Perhaps the most important aspect of reserve lands is their high sustainability. The Emergy Sustainability Index (ESI) and Emergy Index of Sustainable Development (EISD) are both measures of sustainability, but from different perspectives. ESI indicates what is sustainable from the standpoint of the larger scale system, whereas, the EISD shows what is sustainable from the local scale. Both ESI and EISD showed that Maipo was the most sustainable system, primarily because it has the lowest environmental loading and the highest yields. Including conservation value in the expression for sustainability results in a 30% increase in the index value for the Yancheng reserve and a 14% increase for the Maipo reserve.

This analysis is one of the first applications of emergy methods to the problem of quantifying the benefits of conservation on an equal basis with those gained from the economic use of the same land. Many improvements are needed including the urgent need to incorporate a detailed evaluation of biodiversity in the expression. In some cases we lacked the detailed information on flows to document a pathway completely, e.g., the material flows associated with the dollar inflows were unknown, so simplifying assumptions were needed and as a consequence some uncertainty was introduced into the results. We believe the effects of these assumptions to be relatively small, because the major emergy inputs were well documented and from past studies we expect them to be accurate to within 10 to 15% of the mean value (Campbell, 2003).

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Appendix

Raw data, units, calculations and references for the annual energy and material flows in Table 1

Notes	Item	Raw data	Units (per year unless noted)	References and assumptions
I. Farm land[a]				
	Area	2.87E+08	m^2	Li et al. (2003)
	Mean annual temperature	287	K	http://forages.oregonstate.edu/organizations/seed/osc/tech-pubs/goat_ch
	Temperature of growing season	296	K	Li et al. (2003)
1	Mean annual solar radiation	1.19E+06	kcal (m^2)	Zhang (1998)
	Albedo	0.3		Zuo et al. (2004)
	Formula for energy from the sun	Area × average solar radiation × (1-Albedo) × 4186 J/kcal		
	Energy	1.00E+18	J	
2	Wind velocity	5	m/s	Zhu et al. (2004)
	Geostrophic wind	8.34	m/s	Reiter (1969)
	Air density	1.23	kg/m^3	
	Drag coefficient on land	2.00E−03		Garratt (1977)
	Seconds in a year	3.15E+07	s	
	Energy formula	Area × density × drag coefficient × (geostrophic wind velocity)^3 × second seconds/y		
	Energy	1.29E+16	J	
3	Earth heat flux	75	mW (m^2)	http://www.heatflow.und.edu
	Energy formula	Heat flux × area × second seconds/y		
	Energy	6.79E+14	J	
4	Rainfall	1.025	m	
	Mean elevation	2	m	
	Density	1.00E+03	kg/m^3	
	Gravity	9.8	m/s^2	
	Geopotential energy of rain	Area × mean elevation × rainfall × density × gravity		
	Energy	5.77E+12	J	
5	Gibbs free energy of rain formula	(8.314 J/mol/°)(287 K)/(18 g/mol)ln(999,990 ppm/965,000 ppm)		
	Gibbs free energy per gram	4.72	J/g	At mean annual temperature
	Chemical potential energy of rain	Area × rainfall × density × Gibbs free energy		
	Energy	1.39E+15	J	
6	River water inflow	4.70E+09	m^3	
	Density	1.00E+06	g/m^3	
	Mineral content	7.50E+02	ppm	Yancheng Reserve Committee (2000)
	Gibbs free energy of river water	(8.314 J/mol/°)(287 K)/(18 g/mol)ln((1E6- 750)ppm/965,000 ppm)		
	Gibbs free energy at 287 K	4.62	J/g	Average annual temperature
	Energy formula	Volume flow × density × Gibbs free energy		
	Energy	2.17E+16	J	
7	River water for irrigation	0.61	m^3 (m^2)	Bai (2006)
	Gibbs free energy river water	(8.314 J/mol/°)(296 K)/(18 g/mol)ln((1e6- 750)ppm/965,000 ppm)		
	Gibbs free energy at 296 K	4.77	J/g	Avg. temp. growing season
	Energy	8.35E+14	J	For 1.75E+08 m^3
8	Purchased input	1.45E+16	sej/ha	Bai (2006) converted to 9.26 base Lan and Odum (1994), for Tr. Chinese labor and service
	Total purchased emergy	Area × purchased emergy density		
	Emergy purchased	4.16E+20	sej	

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Appendix – continued

Notes	Item	Raw data	Units (per year unless noted)	References and assumptions
9	Productivity of rice	4457	kg/ha	Bai (2006)
	Rice harvested	1.28E+08	kg	
	Energy value	14,230	J/g	Bai (2006)
	Energy of rice harvest	1.82E+15	J	
10	Rice left after harvest	50,000	kg	Dong et al. (2005)
	Energy left	7.12E+11	J	
11	River water outflow	Available energy in river water minus irrigation use		
	Energy	2.09E+16	J	4.52E+09 m^3
II. Aquaculture ponds				
	Area	2.51E+08	m^2	
1	Mean annual solar radiation	1.19E+06	kcal (m^2)	Zuo et al. (2004)
	Albedo	0.3		Zuo et al. (2004)
	Energy formula	Area × average solar radiation × (1-Albedo) × 4186 J/kcal		
	Energy	8.75E+17	J	
2	Wind velocity (metric)	5	m/s	Zhu et al. (2004)
	Geostrophic wind	8.34	m/s	Reiter (1969)
	Air density	1.23	kg/m^3	
	Drag coefficient over water	1.00E−03		Garratt (1977)
	Seconds in a year	3.15E+07	s	
	Energy formula	Area × density × drag coefficient × (geostrophic wind velocity)^3 × second seconds/y		
	Energy	5.64E+15	J	
3	Earth heat flux	75	mW (m^2)	http://www.heatflow.und.edu
	Energy formula	Heat flux × area × second seconds/y		
	Energy	5.94E+14	J	
4	Rainfall	1.025	m	
	Mean elevation	2	m	
	Density	1.00E+03	kg/m^3	
	Gravity	9.8	m/s^2	
	Geopotential of rain	Area × mean elevation × rainfall × density × gravity		
	Energy	5.04E+12		
5	Gibbs free energy of rain	4.73	J/g	At average annual temperature
	Chemical potential of rain	Area × rainfall × density × Gibbs free energy		
	Energy	1.21E+15	J	
6	River water inflow	2.09E+16	J	From I.10 above
7	River water for aquaculture	4.5	m^3 (m^2)	Liu and Luan (2000)
	Energy	5.39E+15	J	1.13E+09 m^3
8	Mean NPP of phytoplankton	5320	g (m^2)	Zuo et al. (2004)
	Standard energy value	5	kcal/g	Parsons and Takahashii (1973)
	Energy formula	Area × average NPP of phytoplankton × standard energy		
	Energy	2.79E+16	J	
9	N fertilizer	30	kg/ha	Liu and Luan (2000)
	Total quantity	7.53E+05	kg	
10	P fertilizer	45	kg/ha	Liu and Luan (2000)
	Total quantity	1.13E+06	kg	
11	Forage	7000	kg/ha	Liu and Luan (2000)
	Total quantity	1.76E+08	kg	
12	Fry	636	kg/ha	Liu and Luan (2000)
	Total quantity	1.60E+07	kg	
13	Electricity and other purchased input	2.73E+15	sej/ha	Lu et al. (2002a)
	Total quantity	6.85E+19	sej	
14	Aquaculture productivity	2500	kg wwt./ha	Liu and Luan (2000)
	Energy value for cultured fish	4813	J/g	http://www.seagrant.wisc.edu/greatlakesfish/ctable/html
	Aquaculture output	Area × productivity × standard energy		
		3.02E+14	J	

Appendix – continued

Notes	Item	Raw data	Units (per year unless noted)	References and assumptions
15	Benthic fauna left in pond	194	g wwt. (m^2)	Dong et al. (2005)
	Standard energy value	3767	J/g wwt.	USDA Nutrient Data Laboratory "Food Composition and Nutrition." http://www.nal.usda.gov/fnic/cgi-bin/nut_search.pl
	Aquaculture output	Area × productivity × dry ratio × standard energy		
		1.83E+14	J	
16	Annual increase of organic matter (OM) in mud	170	g dwt. (m^2)	Liu and Luan (2000)
	Standard energy value	5.00E+00	kcal/g	Gorham and Sanger (1967)
	Energy	8.93E+14	J	
17	River water outflow	Available river water-irrigation		
	Energy	1.55E+16	J	3.40E+09 m^3
III. Phragmites and Aeluropus				
	Area[b]	2.47E+08	m^2	
	Area of *Phragmites*	1.07E+08	m^2	Li (2000)
	Area of *Aeluropus* and*Imperata*	1.40E+08	m^2	Li (2000)
1	Mean annual solar radiation	1.19E+06	kcal (m^2)/y	Zhang (1998)
	Albedo	0.3		Zuo et al. (2004)
	Energy	Area × average of solar radiation × (1-Albedo) × 4186 J/kcal		
	Energy	8.61E+17	J	
2	Wind velocity (metric)	5	m/s	Zhu et al. (2004)
	Geostrophic wind	8.34	m/s	Reiter (1969)
	Air density	1.23	kg/m^3	
	Drag coefficient	2.00E−03		Garratt (1977)
	Seconds/y	3.15E+07	J	
	Energy formula	Area × density × drag coefficient × (geostrophic wind velocity)^3 × second seconds/y		
	Energy	1.11E+16		
3	Earth heat flux	75	mW (m^2)	http://www.heatflow.und.edu
	Energy formula	Heat		flux × area × second seconds/y
	Energy	5.84E+14	J	
4	Rainfall	1.025	m	
	Mean elevation	2	m	
	Density	1.00E+03	kg/m^3	
	Gravity	9.8	m/s^2	
	Geopotential of rain	Area × mean elevation × rainfall × density × gravity		
	Energy	4.96E+12	J	2.41E+8 m^3
5	Gibbs free energy of rain	4.72	J/g	At mean annual temperature
	Chemical potential of rain	Area × rainfall × density × Gibbs free energy		
	Energy	1.20E+15	J	
6	River water inflow	1.55E+16	J	From II. 17 above
7	Evapotranspiration of *Phragmites*			
		NPP = 2.72E3	g (m^2)	Li et al. (2004)
	Water evapotranspired	700 × NPP or 1.90E+06	g (m^2)	Li et al. (2004)
	Gibbs free energy of rain and river	(8.314 J/mol/°)(296 K)/(18 g/mol)ln((1E+6 − 698)/965,000 ppm)		
	Gibbs free energy at 296 K	4.78	J/g	Temp. growing season
	Energy of evapotranspiration	Area × evapotranspiration per area × Gibbs free energy		
	Evapotranspiration of *Phragmites*	1.07E+8m^2 × 700 × 2. 72E+3 g (m^2)/y × 4.78 J/g		
	Energy	9.74E+14	J	2.04E+08 m^3
	Evapotranspiration of *Aeluropus* and *Imperata*	(1–22%) × pan		evaporation = 78% × 1.5355 m
	Xu et al. (2006)			
	Energy of evapotranspiration	Area × evapotranspiration per area × density × Gibbs free energy		
	Calculation	1.40E+8 m^2 × 78% × 1. 5355 m × 1E+6 g/m^3 × 4.78 J/g		

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Appendix – continued

Notes	Item	Raw data	Units (per year unless noted)	References and assumptions
	Energy	8.01E+14	J	1.68E+08 m^3
	Subtotal ET[b,c]	1.78E+15	J	3.71+08 m^3
	ET from rain 0.072 by energy[d,c]	1.27E+14	J	2.65E+07 m^3
	ET from river 0.928 by energy[d,c]	1.65E+15	J	3.51E+08 m^3
8	Water stored in peaty sediment			
	Depth addition of peat	0.04	m	Yancheng Reserve Committee (2000)
	Water content ratio	0.57		Zuo et al. (2004)
	Density	1.00E+06	g/m^3	
	Gibbs free energy of rain & river	4.63	J/g	At average annual temperature
	Energy	Volume of rain water × Gibbs free energy of rain water + vol. of river water × Gibbs free energy of river water		
	Subtotal water stored[2]	2.61E+13	J	5.63E+06 m^3
	Fraction from rain 0.066 by vol.[e,c]	1.76E+12	J	3.72E+05 m^3
	From river water 0.934 by vol.[e,c]	2.43E+13	J	5.26E+06 m^3
9	Cost for harvest per MT *Phragmites*	100	RMB/MT	
	Exchange ratio	8.3	$/RMB in 2000	
	Harvest quantity of *Phragmites*	20,000	MT/y	
	Formulation of Purchased input for harvest *Phragmites*	Cost for harvest per MT *Phragmites*/ Exchange ratio × quantity harvested		
	Purchased input	2.41E+05	$ in 2001	
10	NPP of *Phragmites*[c]	$1.07E+08\ m^2 \times 2.72E+03\ g\ (m^2)/y$		Zuo et al. (2004)
		2.91E+11	g	
	NPP of *Aeluropus* and *Imperata*[c]	$1.40E+08\ m^2 \times 2.45E+03\ g\ (m^2)$		Zuo et al. (2004)
		3.43E+11	g	
	Subtotal	6.34E+11	g	
	Standard energy value	4.00E+00	kcal/g	
	Energy[b]	1.06E+16	J	
	Energy of *Phragmites* harvested[c]	3.35E+14	J	
	Energy of left NPP[c]	1.03E+16	J	
11	Depth of peaty sediment	0.85	m	Yancheng Reserve Committee (2000)
	Density	0.7	g/cm^3	Odum (1996)
	Organic C content ratio	0.105		Odum (1996)
	Standard energy value of C	11	kcal/g	Coultas and Calhoun (1976)
	Turn over time	188	a	
	Energy formula	Deposition area × depth × density × C content ratio × Gibbs free energy of the C/turn over time		
	Energy	3.78E+15	J	
12	Annual production of benthic fauna	378	g wwt. (m^2)	Dong et al. (2005)
	Standard energy value	3767	J/g	USDA Nutrient Data Laboratory "Food Composition and Nutrition." http://www.nal.usda.gov/fnic/cgi-bin/nut_search.pl
	Energy formula	Area × biomass per area × standard energy value		
	Energy	3.52E+14	J	
13	River water outflow	1.38E+16	J	3.04E+09 m^3
14	Rain infiltration[f]	1.07E+15	J	
IV. Spartina and Suaeda				
	Area[2]	5.17E+08	m^2	
	Area of *Spartina*	2.51E+08	m^2	
	Area of *Suaeda*	2.66E+08	m^2	
1	Mean annual solar radiation	1.19E+06	kcal (m^2)	Zhang (1998)
	Albedo	0.3		Zuo et al. (2004)
	Energy formula	Area × average of solar radiation × (1-Albedo) × 4186 J/kcal		
	Energy	1.80E+18	J	
2	Wind velocity (metric)	5	m/s	Zhu et al. (2004)
	Geostrophic wind	8.34	m/s	Reiter (1969)

Appendix – continued

Notes	Item	Raw data	Units (per year unless noted)	References and assumptions
	Air density	1.23	kg/m^3	
	Drag coefficient	2.00E−03		Garratt (1977)
	Seconds/y	3.15E+07	s	
	Energy of wind	Area × density × drag coefficient × (geostrophic wind velocity)^3 × second seconds/y		
	Energy	2.32E+16	J	
3	Earth heat flux	75	mW (m^2)	http://www.heatflow.und.edu
	Energy	Heat flux × area × second seconds/y		
	Energy	1.22E+15	J	
4	Rainfall	1.025	m	
	Mean elevation	2	m	
	Density	1.00E+03	kg/m^3	
	Gravity	9.8	m/s^2	
	Geopotential of rain	Area × mean elevation × rainfall × density × gravity		
	Energy	1.04E+13		
5	Gibbs free energy of rain	4.72	J/g	At mean annual temperature
	Chemical potential of rain	(Area + 0.5 prograded area) × rainfall × density × Gibbs free energy		
	Energy	2.50E+15	J/y	5.30E+08 m^3
6	River water inflow	1.38E+16	J/y	From III.13
7	Evapotranspiration	3.5	L (m^2)/growth day	Hussey and Odum (1992)
	Growth days (without frost)	210	day	
	Density	1.00E+03	g/l	
	Subtotal energy ET[b,c]	1.85E+15	J	3.80E+08 m^3
	From rain fraction 0.155 by energy[d,c]	2.83E+14	J	5.81E+07 m^3
	From river water 0.845 by energy[d,c]	1.57E+15	J	3.28E+08 m^3
8	Water stored in peaty sediment			
	Depth addition of peat	0.04	m	Yancheng Reserve Committee (2000)
	Water content ratio	0.57		Zuo et al. (2004)
	Density	1.00E+06	g/m^3	
	Energy formula	Volume of rain water × Gibbs free energy of rain water + volume of river water × Gibbs free energy of river water		
	Subtotal energy of water stored[b]	5.47E+13	J	1.18E+07 m^3
	From rain fraction 0.153 by vol.[e,c]	8.25E+12	J	1.75E+06 m^3
	From river water 0.847 by vol.[e,c]	4.65E+13	J	1.00E+07 m^3
9	Tides per year	707		
	Mean height	1.7	m	Li et al. (2005)
	Density	1.025E+03	kg/m^3	
	Gravity	9.800E+00	m/s^2	
	Formula for energy of tide	Area × 0. 5 × (tide seconds/y) × (height)^2 × density × gravity		
	Energy	5.50E+15	J	
10	NPP of *Spartina*	Area × 2.60E3 g (m^2)		Zuo et al. (2004)
		6.53E+11	g	
	NPP *Suaeda*	2.66E+08 m^2 × 5.59E+02 g (m^2)		Zuo et al. (2004)
		1.49E+11	g	
	Subtotal salt marsh NPP[b]	8.01E+11	g	
	Standard energy value	4.00E+00	kcal/g	
	Energy	1.34E+16	J	
11	Annual depth of peaty sediment	0.85	m	Chen (1994)
	Density	0.7	g/cm^3	Odum (1996)
	Organic C content ratio	0.105		Odum (1996)
	Standard energy value	11	kcal/g C	Coultas and Calhoun (1976)
	Energy of peat deposited	Area × depth × density × organic content ratio × Gibbs free energy of the organic matter		
	Energy	1.40E+16	J/y	
12	Annual production of benthic fauna	378	g wwt. (m^2)	Dong et al. (2005)
	Standard energy value	3767	J/g wwt.	
	Formula for energy of benthos	(Area + 0.5 prograded area) × biomass per area × standard energy value		
		7.36E+14	J/y	

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Appendix – continued

Notes	Item	Raw data	Units (per year unless noted)	References and assumptions
13	River water outflow	1.22E+16	J/y	2.71E+09 m^3
14	Rain infiltration[f]	2.21E+15	J/y	4.62E+08 m^3
V. Saltpans				
	Area	3.25E+08	m^2	
1	Mean annual solar radiation	1.19E+06	kcal (m^2)/y	Zhang (1998)
	Albedo	0.3		Zuo et al. (2004)
	Formula for energy from the sun	Area × average solar radiation × (1-Albedo) × 4186 J/kcal		
	Energy	1.13E+18	J/y	
2	Wind velocity (metric)	5	m/s	Zhu et al. (2004)
	Geostrophic wind	8.34	m/s	Reiter (1969)
	Air density	1.23	kg/m^3	
	Drag coefficient	1.00E−03		Garratt (1977)
	Seconds/y	3.15E+07	J	
	Formula for energy from the wind	Area × density × drag coefficient × (geostrophic wind velocity)^3 × seconds/y		
	Energy	7.30E+15	J/y	
3	Earth heat flux	75	mW (m^2)	http://www.heatflow.und.edu
	Energy formula	Heat flux × area × seconds/y		
	Energy	7.69E+14	J	
4	Rainfall	1.025	m/y	
	Mean elevation	2	m	
	Density	1.00E+03	kg/m^3	
	Gravity	9.8	m/s^2	
	Geopotential of rain	Area × mean elevation × rainfall × density × gravity		
	Energy	6.53E+12		
5	Formula for weight of rain water	Area × rainfall × density		
	Mass	3.33E+14	g	
	Salt yield	9.36E+11	g	Wang et al. (2001)
	Waste salt	9.36E+10	g	
	Salts in waste brine	6.32E+11	g	
	Salt required	1.66E+12	g	
	Mean salinity of seawater	3.09E+04	g/m^3	
6	Formula for seawater required	Salt dissolved in seawater/mean salinity of seawater		
	Volume	5.38E+07	m^3	
7	Evaporation	1.5355	m/y	Yancheng Reserve Committee (2000)
	Density	1.00E+06	g/m^3	
	Gibbs free energy rain	4.87	J/g	In the warm seasons
	Energy	Area × evaporation × density × Gibbs free energy 2.43E+15 J		
8	Fuels and goods required per g salt	5.09E+07	sej/g salt yield	Babic (2005), adjusted to 9.26 baseline
	Total fuels and goods	4.77E+19	sej/y	
9	Labor	22.4	J/g salt yield	Babic (2005), adjusted to 9.26 baseline
	Labor cost	2.09E+13	J/y	
10	Salt yield	9.36E+11	g	Wang et al. (2001)
11	Annual production of benthic fauna	241	g wwt. (m^2)	Dong et al. (2005)
	Standard energy value	3767	J/g	USDA Nutrient Data Laboratory "Food Composition and Nutrition." http://www.nal.usda.gov/fnic/cgi-bin/nut_search.pl
	Formula for energy of benthos	Area × biomass per area × dry ratio × standard energy value		
	Energy	2.95E+14	J	
VI. Mud flats				
	Area	2.06E+09	m^2	
1	Mean annual solar radiation	1.19E+06	kcal (m^2)/y	Zhang (1998)
	Albedo	0.3		Zuo et al. (2004)
	Energy	Area × average of solar radiation × (1-Albedo) × 4186 J/kcal		
		7.19E+18	J/y	

Appendix – continued

Notes	Item	Raw data	Units (per year unless noted)	References and assumptions
2	Wind velocity (metric)	5	m/s	Zhu et al. (2004)
	Geostrophic wind	8.34	m/s	Reiter (1969)
	Air density	1.23	kg/m^3	
	Drag coefficient	1.00E−03		Garratt (1977)
	Seconds/y	3.15E+07	J	
		Area × density × drag coefficient × (geostrophic wind velocity)^3 × seconds/y		
	Energy	4.64E+16	J	
3	Earth heat flux	75	mW (m^2)	http://www.heatflow.und.edu
	Energy	Heat flux × area × seconds/y		
	Energy	4.88E+15	J	
4	Rainfall	1.025	m	
	Mean elevation	2	m	
	Density	1.00E+03	kg/m^3	
	Gravity	9.8	m/s^2	
	Geopotential of rain	Area × mean elevation × rainfall × density × gravity		
	Energy	4.14E+13		
5	Gibbs free energy of rain	4.72	J/g	At mean annual temperature
	Formula for rain chemical potential	Area × rainfall × density × Gibbs free energy		
	Energy	9.98E+15	J	2.11E+09 m^3
6	River water inflow	2.71E+15	g	From IV.13 above
	Salinity of mixed water near beach	2.20E+04	g/m^3	Yancheng Reserve Committee (2000)
	Formula for Gibbs free energy	(8.314/mol/°)(287 K)/(18 g/mol)ln(1E+06 − 750)ppm/(1E+06 − 22,000 ppm)		
	Gibbs free energy river water	2.85	J/g	
	Energy	7.71E+15	J	
7	Wave			
	Shore length	5.82E+05	m	
	Absorption ratio	0.125		Odum (1996) and Qin et al., 2000
	Density	1.025E+03	kg/m^3	
	Mean wave height	1	m	Li (2000)
	Gravity	9.8	m/s	
	Velocity	2.6	m/s	
	Formula for wave energy	Shore length × absorption ratio × density × gravity × (height)^2 × velocity × 3.15 × 107 seconds/y		
	Energy	5.99E+16	J/y	
8	Tides per year	707		
	Mean height	1.7	m	
	Density	1.025E+03	kg/m^3	
	Gravity	9.800E+00	m/s^2	
		Area elevated × 0.5 × (tide seconds/y) × (height)^2 × density × gravity		
	Energy	2.12E+16	J/y	
9	NPP of phytoplankton	5320	g (m^2)	Zuo et al. (2004)
	Standard energy value	5	kcal/g	
		Area × average NPP of phytoplankton × standard energy		
	Energy	2.30E+17	J	
10	Annual production of Benthic fauna	365	g (m^2)	Dong et al. (2005)
	Standard energy value	3767	J/g	USDA Nutrient Data Laboratory “Food Composition and Nutrition.” http://www.nal.usda.gov/fnic/cgi-bin/nut_search.pl
		Area × biomass per area × standard energy value		
	Energy	2.84E+15	J/y	
Waterfowls				
1	Purchased forage for waterfowl (mainly corn)	5.00E+06	g/y	Dong et al. (2005)
	Energy per weight	19,736	J/g	Campbell et al. (2005)
	Energy	9.87E+10	J	

(*continued on next page*)

Appendix – continued

Notes	Item	Raw data	Units (per year unless noted)	References and assumptions
2	Estimated number of birds	7.54E+06	ind.	Yancheng Reserve Committee (2000)
	Mean weight	800	g/ind.	Qin et al. (2000)
	Time of stay (years)	0.5		Yancheng Reserve Committee (2000)
	Dry weight ratio	0.2		
	Standard energy value	4.04	kcal/g	Typical value for duck
		Number × average weight × time of stay × dry wwt ratio × standard energy value		
	Energy	1.02E+13	J	
3	Daily food requirement of waterfowl	Food weight/average biomass of waterfowl/day		
	Daily ration	8/45	g/g.day	Loesch et al. (2002),
	Benthic fauna eaten by waterfowl	Number × average weight × Stay in days × daily ration-artificial forage–rice		
	Weight Fauna consumed[g]	1.96E+11	g	
	Fraction of benthic fauna eaten by waterfowl	16.79%		

Subsystems are given by Roman numerals from I to VI progressing toward the sea.

a Assumes all of the farmland is used for rice planting and is irrigated.

b Sub-items included.

c Assume the chance that a parcel of river or rain water would be used for evaporation, evapotranspiration or absorption into the peat was dependent only on the quantities of each that were available.

d Take the available energy of river water and rain water as the weighting factor.

e Take the available volume of river water and rain water as the weighting factor.

f Assume all of the rain water left after evapotranspiration was assumed to infiltrate into the ground water in the relatively flat

g 2.25E+11 g food required and 1.52E+12 g produced.

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