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New emergy indices for sustainable development

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Abstract: The emergy indices for the evaluation of system's sustainable development ability were studied. Results indicated that the emergy indices are simplified and merged, and a new emergy index for sustainable development(EISD) is deduced. Employing EISD, two cases are conducted. The first one is to compare three different dike-pond agro-ecological engineering modes, which are: melon-melon-cabbage-four domestic fishes(mode Ⅰ), melon-melon-cabbage-pig-four domestic fishes (mode Ⅱ) and melon-melon-cabbage-pig-four domestic fishes combined with *Siniperca chuatsi B*.(mode Ⅲ). The result is that the EISD of mode Ⅰ is 0.53. Mode Ⅱ's EISD is 5.26 times of mode Ⅰ, and mode Ⅲ's EISD is 6.83 times of mode Ⅰ. The second one is to evaluate the development of Zhongshan City, Pearl Delta, during 1996 to 2000. The result indicated that the EISD of Zhongshan had appreciably declined from 1996 to 1998, and quickly improved from 1998 to 2000, partly because of its environment protection and product construction. Both of the two cases studies showed that EISD can assessment the sustainable development ability more roundly, with the consideration of environmental impact and social-economic effect at the same time.

Keywords: indices; emergy; sustainable development

Introduction

A central point and advancing problem in sustainable development study is how to evaluate the system's sustainable development ability quantitatively. Researchers have tried to solve this problem in different ways(Liu, 1999; Liverman, 1988), but most of them staying in the separate accounting levels. They are not able to consider both the system's environmental impact and the social-economic effect at the same time.

Emergy analysis theory was founded by H.T.Odum, at the end of the 80's of the 20th century. With the unified unit, emergy theory can bridge the natural system and social-economic system, and can evaluate a system's sustainable development ability thoroughly. Ecologists and economical ecologists have applied the theory all over the world(Huang, 1991; Ulgiati, 1994; Brown, 1997; Lan, 1998; Yan, 1998; Sui, 1999; Zhang, 1999; Odum, 2000), and the trend is continuous. But, as a young theory, its indices are not perfect yet. Based on the correlation analysis among several main indices the emergy indices system is simplified and combined. A new emergy index for sustainable development is deduced, followed with two case studies of three dike-pond agro-ecological engineering modes and Zhongshan City, Pearl Delta.

1 Correlation study among main current emergy indices

Although the emergy indices are different when different systems are studied, there are some main current emergy indices, such as emergy yield ratio(EYR), emergy investment ratio(EIR), emergy exchange ratio(EER), emergy amplifier ratio(EAR), emergy self-support ratio(ESR), environmental loading ratio(ELR), renewable resource investment ratio(RIR) and so on.

There are some correlation among part of these indices above, such as EYR, EIR and ESR and so on. According to the separate principle of indices system, there should not be any correlation among the indices belonging to the same indices system. If there is some correlation, these indices should be simplified or combined. Employing the concepts given out by H.T.Odum(Odum, 1996) and the symbols

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are shown in Fig. 1, the concept and the correlation among those above emergy indices are studied as follows:

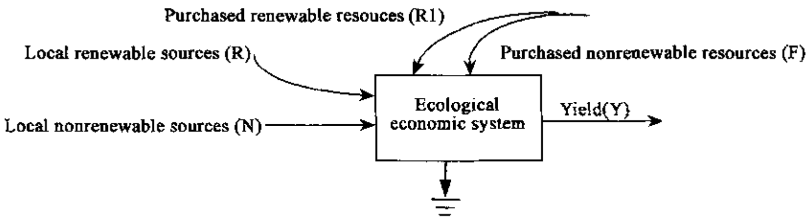

Fig. 1 The emergy input and output diagram of an ecological-economic system

1.1 EYR, EIR and ESR

EIR is the ratio of emergy (F + R1) feed back from the outside of the system to the indigenous emergy inputs (N + R). The equation is:

$$\mathrm{EIR} = (F + R1)/(N + R). \tag{1}$$

EYR is the ratio of the emergy of the output Y divided by the emergy inputs which are fed back from the outside of the system under study(F + R1):

$$\mathrm{EYR} = Y/(F + R1)$$

$$= (N + R + F + R1)/(F + R1) \tag{2}$$

$$= 1 + (N + R)/(F + R1). \tag{3}$$

Substituting Eq.(1) into Eq.(3):

$$\mathrm{EYR} = 1 + 1/\mathrm{EIR}. \tag{4}$$

The ESR is the percentage of the total emergy driving a system that is derived from indigenous emergy inputs. The equation is:

$$\mathrm{ESR} = (N + R)/Y$$

$$= (N + R)/(N + R + F + R1) \tag{5}$$

$$= (N + R + F + R1 - F - R)/(N + R + F + R1)$$

$$= 1 - (F + R1)/(N + R + F + R1). \tag{6}$$

Substituting Eq.(2) into Eq.(6):

$$\mathrm{ESR} = 1 - 1/\mathrm{EYR}. \tag{7}$$

From Eq.(5):

$$1/\mathrm{ESR} = 1 + (F + R1)/(N + R). \tag{8}$$

Substituting Eq.(1) into Eq.(8):

$$1/\mathrm{ESR} = 1 + \mathrm{EIR}. \tag{9}$$

From the above Eqs. (4), (7), (9), we can know that the EYR is the sum of 1 and the reciprocal of EIR, and is inversely proportional to EIR. ESR is the difference of 1 and the reciprocal of EYR, and is directly proportional to EYR. EIR is the detraction of the reciprocal of ESR and 1, and is in inverse proportion to ESR.. Obviously, there are direct correlations among these three emergy indices. The three indices have the similar function in assessment, so they should be combined and just keep one of them. Since EYR is used more frequently and is similar to the classical economic index, i.e. output/input, we suggest to keep EYR in the emergy indices system.

1.2 ELR and RIR

ELR is the ratio of all the nonrenewable emergy input(F + N) to the renewable emergy input (R + R1):

$$\mathrm{ELR} = (F + N)/(R + R1). \tag{10}$$

RIR is the percentage of the total emergy driving a system which is derived from the renewable resources:

$$RIR = (R + Rl)/Y = (R + Rl)/(N + F + R + Rl), \quad (11)$$

inverting both sides of the equation:

$$1/RIE = 1 + (N + F)/(R + Rl). \quad (12)$$

Bringing Eq.(10) into Eq.(12):

$$1/RIR = 1 + ELR. \quad (13)$$

From Eq.(13) we can know that the reciprocal of RIR is the sum of 1 and the ELR, and is inversely proportional to ELR. The two indices have the similar function in assessment, so they should be combined and just withhold one of them. Considering the perspicuity of environmental impact, we suggest to keep ELR in the emergy indices system.

2 New emergy indices for sustainable development

EYR is suitable to evaluate a system's yield efficiency. ELR is suitable to assess the system's environmental impact. But there still lack a multiple index to evaluate the system's sustainable development ability roundly in emergy indices system, even after the combination. To solve this problem, Brown and Ulgiati(Brown, 1997) have published a paper on emergy indices for sustainable development recently. They defined the new index as EYR/ELR, and named it ESI(emergy sustainable index). Through a case study, they quantified the ESI as: when ESI > 10, it means environmental overloading; when 10 > ESI > 1, it means developing economies; when 1 > ESI, it means developed economies. There are two points that have been neglected by them: (1) Although all the output of a system is valuable in the point of ecology, our current knowledge and technology is limited to makeing use of them ultimately. So all the outputs of a system are not economic to our ecological-economic system and have plus benefit. Some of them even become troublesome and have negative benefit, such as castoff and pollution etc. So, not all the high EYR is beneficial and helpful to our sustainable development; (2) EER is influenced by market, culture and ethics etc., and is decided by time and location too. Therefore, even the same EYR can have different influences on the system's sustainable development.

With the growth of the people's ability, the pure natural ecosystem has shrunk quickly, instead of the dramatic extending of diverse ecological-economic systems. These ecological-economic systems have multiple characteristics. They have both the characteristics of the natural ecosystem and the mark of the human behavior, controlled by natural law and the human's subjective activity at the same time. The multiple characteristics require us to take into account both the objective environmental impact and the actual function in our human economic society simultaneously, when the sustainable development ability of a system is evaluated.

Hold in 1992, the world convention for sustainable development defined sustainable development as the development both accommodating modern need and not harming our offspring's ability to accommodate their need, and achieving the society's economic growth, structure perfection and the natural resource's sustainability, optimum natural environment at the same time, namely harmonious development of the economy, society, resource and environment. This definition has two connotations: firstly, the social-economic must be developed quickly; secondly, the natural environment must be sustainable. The social-economic development requires the system's emergy output has high benefit for us. Simply speaking, the EYR × EER must be high. The natural environment's sustainability requires ELR to be low.

The system's EER is all the emergy contained in the money which is got from the material or abstract trade with the emergy traded out.

From the above discussion we know that there is no correlation among these three emergy indices. So, we can combine them to get a multiple indices for sustainable development which can take into consideration the system's social economic benefits and the natural environmental impact at the same time. Considering that the social economic benefit is directly proportional to the system's sustainable development and the ELR is inversely proportional to the system's sustainable development, we put the EYR × EER as the numerator, and put the ELR as the denominator, to construct a new emergy index named EISD(emergy index for sustainable development). EISD is directly proportional to the system's sustainable development ability. It can be expressed as:

$$\mathrm{EISD} = \mathrm{EYR} \times \mathrm{EER}/\mathrm{ELR}.$$

The higher the EISD is, the higher the social economic benefit per unit environmental loading we can get, the more comparable in sustainable development the system is.

Employing the margin-benefit-analysis method of the economy into the system's optimum analysis, we can use EAR(emergy amplifier ratio) to replace the emergy yield ratio, and use the new index to evaluate the EISD margin benefit of every unit emergy margin cost. We named it as ΔEISD(margin EISD benefit) for the system's sustainable development.

$$\Delta\mathrm{EISD} = \mathrm{EAR} \times \mathrm{EER}/\mathrm{ELR}.$$

The higher the EISD margin is, the higher the direct effect of the system's emergy margin cost is.

Associated with the ETR(emergy transformation ratio), EER, EAR, ELR and ΔEISD, EISD can be used in the following two aspects: (1) used in transverse comparison study of different systems which have the same output. The higher the EISD is, the more comparable the system is, in the long time scale of sustainable development; (2) used in fore-and-aft optimizing accounting of a current or burgeoning system. Based on the original system, the system's EAR and EER can be improved, and its dependence on nonrenewable resource can be minimized, through the continuous introduction of new technical innovations. Finally, the benefit per unit environmental loading ratio can be improved and the system's optimization can be achieved.

3 Two case studies

3.1 The assessment of three different dike-pond modes

There is a long history of the dike-pond mode in South China. The new typical dike-pond modes are developed from traditional dike-pond modes by farmers to suit the needs of the market. These new burgeoning agro-ecological engineering modes have made notable economic benefits, social benefits and ecological benefits. They are the typical models of Chinese agro-ecological engineering modes. It's very meaningful to study them systematically both in theory and in practice.

Using the new emergy index for sustainable development(EISD), we select three typical dike-pond modes in South China, to conduct a comparison study of their sustainable development ability. The three typical dike-pond modes are melon-melon-cabbage-four domestic fishes (Mode Ⅰ), melon-melon-cabbage-pig-four domestic fishes(mode Ⅱ) and melon-melon-cabbage-four domestic fishes combined with *Siniperca chuatsi B*.(mode Ⅲ). With the same dike area/pond area ratio and pond depth, 3/7 and 1.5 m, the areas of the three modes are 6.7 hm^2 (mode Ⅰ), 7.6 hm^2 (mode Ⅱ) and 9.5 hm^2 (mode Ⅲ). Their emergy flow is shown in Fig.2, as indicated above.

The cultivation procedure is as follows:

From the beginning of February to the beginning of June, plant and harvest the first batch of *Benincasa hispida Cong*, with the planting density of 749.63 body/hm^2. From the beginning of June to the beginning of September, plant and harvest the second batch of *Benincasa hispida Cong*. From the beginning of September to the end of November, plant and harvest *Biassica Oleracea L. Var. Capitata L.* The four domestic fishes are put into the pond at the end of December the previous year, with the density

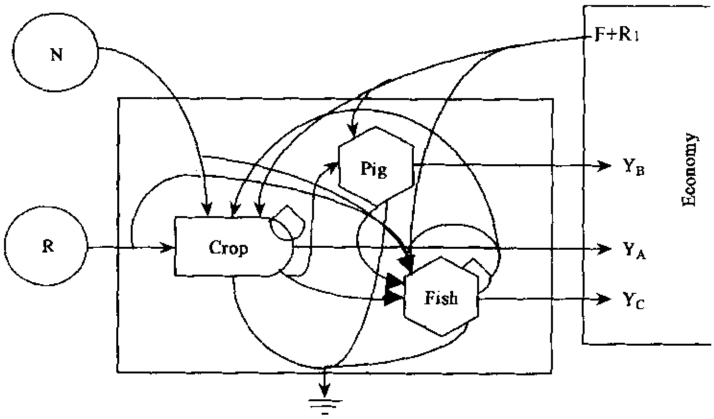

Fig.2 The emergy flow diagram of the 3 dike-pond modes
N. the nonrenewable local resources input; R. the renewable local resources input; F. the nonrenewable purchased resources input; R1. the renewable purchased resources input; Y_A. the output of the crop on dike; Y_B. the output of the pig on dike; Y_C. the output of the fish in pond

of 299.85 *Ctenopharyngodon idella*/hm^2, 44.98 *Hypophthalmichthys molitrix*/hm^2, 74.96 *Aristichthys nobilis*/hm^2, 4497.75 *Cirrhina militorella*/hm^2, 29.99 *Cyprinus carpio*/hm^2 and 149.93 *Carassius auratus*/hm^2. At the end of July, harvest the first batch of *Aristichthys nobilis*, and put into the second batch *Aristichthys nobilis* with the same density. At the beginning of December, harvest all the fish and dry the pond. All of the crop byproduct, such as melon seedlings and waste cabbage, is put into the pond as the forage for fish. 80% of the pond-mud is fed back to the dike as manure for the crop, the other is reserved in the pond.

Based on mode Ⅰ, a pig-breeding-subsystem is introduced into mode Ⅱ's dike, with the density of 4.69 body/hm^2 and 2 batch/a. From 12.5 kg/body breeding to 100 kg/body, the breeding time of each batch pig is 120 days. All of the pork is sold in the market to get economic benefit, and all of the pig excrements are put into the pond as forage for fish to decrease the fish-forage cost.

Table 1 The comparison of emergy input and output among three dike-pond modes

Item	Mode Ⅰ	Mode Ⅱ	Mode Ⅲ
Renewable local resources emergy input[a] (R), sej/a	8.60E+14	9.80E+14	1.23E+15
Renewable purchased resources emergy input[b] (R1), sej/a	3.33E+16	2.84E+17	3.67E+17
Nonrenewable local resources emrgy input[c] (N), sej/a	4.96E+13	5.64E+13	7.08E+13
Nonrenewable purchased resources emergy input[d] (F), sej/a	1.20E+17	1.36E+17	1.73E+17
Emergy yield (Y), sej/a	1.54E+17	4.20E+17	5.42E+17
Economic benefit got from product sale, RMB Yuan/a	50947	100016	164470

[a] R = maxim of solar radiation emergy, wind emergy, rain chemical emergy, rain potential emergy and earth cycle emergy = rain chemical emergy = area × rainfall × rain density × Gibbs number × ETR (Odum, 1996) = (__ m^2)(1.6916 m/a)(1000 kg/m^3)(4.94E+03J/kg)(1.54E+04 sej/J)

[b] $R1 = \sum_{i=1}^{n} R1i \sum_{i=1}^{n}$ (renewable purchased input i × ETRi)

[c] N = erosion of the surface soil emergy = area × erosion ratio of the surface soil × organic percent of soil × energy of unite soil organic × ETR = (__ m^2)(2.00E+02 g/(m^2.a))(2.63E−02)(5.40 kcal/g)(4186 J/kcal)(6.25E+04 sej/J)

[d] $F = \sum_{i=1}^{n} F_i \sum_{i=1}^{n}$ (nonrenewable purchased input i × ETRi)

Based on mode Ⅱ, a batch of *Siniperca chuatsi B*. is introduced into mode Ⅲ's pond in July, with the density of 449.78 body/hm^2, and is harvested at the beginning of December with other fishes. This addition can improve the pond-mud both in quantity and in quality. With higher market price, the introduction of *Siniperca chuatsi B*. improved the system's economic benefits dramatically.

Based on Table 1 and the concept of the above mentioned emergy indices, we can deduce out some corresponding indices shown in Table 2. Under the highest environmental pressure, mode Ⅰ's sustainable development ability is the lowest one, and its EISD is only 0.53. Mode Ⅱ's environment pressure is lower but its emergy exchange is the lowest. Finally, mode Ⅱ's EISD is 5.26 times of mode Ⅰ, and it's sustainable development ability is medium. With the lower environmental pressure and higher emergy exchange ratio, Mode Ⅲ is the best in sustainable development ability, and its EISD is 6.83 times of mode Ⅰ.

Table 2 The comparison of emergy indices among the three dike-pond modes

Indices	Mode Ⅰ	Mode Ⅱ	Mode Ⅲ
Emergy yield ratio(EYR)	1.00E+00	1.00E+00	1.00E+00
Environmental loading ratio(ELR)	3.51E+00	4.77E-01	4.70E-01
Emergy exchange ratio(EER)	1.85E+00	1.33E+00	1.70E+00
Emergy indices for sustainable development(EISD)	5.30E-01	2.79E+00	3.62E+00
System's emergy transformity(ETR)	1.08E+06	1.46E+06	1.45E+06
Breeding subsystem's margin EISD benefit(ΔEISD1)	—	1.57E-16	1.57E-16
Siniperca chuatsi B.'s margin EISD benefit(ΔEISD2)	—	—	1.36E-15
EMERGY sustainable indices(ESI)	2.85E-01	2.10E+00	2.13E+00

The ΔEISD of putting pig-breeding subsystem into mode Ⅰ, as mode Ⅱ and mode Ⅲ, is 1.57E-16/(sej·hm^2). The ΔEISD of putting *Siniperca chuatsi B*. into four-domestic-fish pond, as mode Ⅲ, is 1.36E-15/(sej·hm^2). Compared with the pig-breeding subsystem, the plus effect of putting *Siniperca chuatsi B*. into four-domestic-fishes-pond is much more remarkable.

3.2 Evaluation of Zhongshan City, Pearl Delta

With the improving urbanization of the whole world and the consequently serious pollution problem, urban ecology study has become one of the main direct of ecology study. As an developing country, China must be serious to choose its owe way to realize urbanization and sustainable development at the same time. We choose Zhongshan City, Pearl Delta here, as a case to study the change of its sustainable development ability from 1996 to 2000.

Table 3 The input and output of Zhongshan City ecosystem from 1996 to 2000

Item	1996	1997	1998	1999	2000
Renewable local resources emergy input (R), 10^{20}sej/a	2.6100	2.5800	2.5200	2.5200	2.5200
Renewable purchased resources emergy input (R1), 10^{21}sej/a	2.7230	2.5120	3.1210	4.4630	5.6030
Nonrenewable purchased resources emergy input d (F), 10^{22}sej/a	1.5744	1.5927	1.7921	2.0282	2.1528
Emergy yield (Y), 10^{22}sej/a	1.8728	1.8697	2.1294	2.4997	2.7383
GDP, 10^9 USD/a	2.3160	2.6650	3.0080	3.2930	3.7780
The emergy/ RMB Yuan, 10^{12}sej/USD	6.7905	6.1872	5.7371	5.4828	4.9409

From the input and output data mentioned in Table 3, we can get the consequent emergy indices of Zhongshan City ecosystem from 1996 to 2000(Table 4). From Table 4 we can see that, as a whole, the sustainable development ability of Zhongshan City ecosystem had appreciably declined during 1996 to 1998 with its EISD decreased from 0.1614 to 0.1544, and quickly improved during 1998 to 2000 with its EISD increased from 0.1544 to 0.1871. We can analysis this trends from the following three sides. First, the consume structure of Zhongshan City was less and less depended on nonrenewable resource come from local natural or purchasing, with its ELR decrease from 5.2761 in 1996 to 3.6769 in 2000. Second, the decreasing of EYR of Zhongshan City shows that Zhongshan City is more and more depended on the purchased input, and the percent of renewable resource in purchased input had inceresed during 1997 to 2000. Third, the EER of Zhongshan City had decreased from 1997 to 2000, partly because of its product construction and the influence of economic decline of the whole world. Zhongshan City should pay more attention to adjust its product construction so that it can get rational economic reward from the market, and showing its accomplishment in environment protection and development completely.

Table 4 The emergy indices of Zhongshan City ecosystem from 1996 to 2000

Item	1996	1997	1998	1999	2000
Emergy yield ratio(EYR)	1.0141	1.0141	1.0120	1.0102	1.0093
Environmental loading ratio(ELR)	5.2761	5.7498	5.3131	4.3016	3.6769
Emergy exchange ratio(EER)	0.8398	0.8819	0.8104	0.7223	0.6817
Emergy indices for sustainable development(EISD)	0.1614	0.1555	0.1544	0.1696	0.1871
Emergy sustainable indices(ESI)	0.1922	0.1764	0.1905	0.2348	0.2745

4 Conclusions

Pay attention to show the social-economic benefit under unit environment impact, EISD can show the sustainable development ability of the system under study more roundly, with the considering of social-economic benefit and environment impact at the same time. The analysis of EISD and its three subindices can supply more reference for the policy maker to realize sustainable development. EISD is more sensitive in the assessment of the system's sustainable development ability and in the discovery of the system's development result. EISD can be used to evaluate all kinds of economic ecosystems, from agricultural ecosystem to urban ecosystem, and can evaluate both the steady conditions and dynamic change of different economic ecosystems.

Put the first case study into consideration, mode Ⅰ's sustainable development ability is the lowest, but it is still popular in practice, just because its EER and economic benefit is higher. Under the similar environmental pressure, the introduction of *Siniperca chuatsi B*. into four-domestic-fishes-pond can promote the whole system's social economic benefit and sustainable development ability dramatically. To the second case study, the sustainable development ability of Zhongshan City had appreciably declined during 1996 to 1998, and quickly improved from 1998 to 2000, partly because of its environment protection and product construction. Zhongshan City should pay more attention to adjust its product construction so that it can get rational economic reward from the market, and showing its accomplishment in environment protection and development completely. Comparing the two cases studies, we can see that, with more applying of ecology principles, the EISD of dike-pond agri-ecological engineering modes is much higher than the EISD of city, even comparing with the Zhongshan City which is one of the six ecological cities of China. So with the accelerated urbanization of our country, we should applying more ecology principles into the development of urban systems.

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