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Integrated emergy and economic evaluation of lotus-root production systems on reclaimed wetlands surrounding the Pearl River Estuary, China

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ABSTRACT

Lotus (*Neumbo nucifera*, Gaertn) is the most important aquatic vegetable in China, with a cultivation history of over 3000 years. The emergy, energy, material, and money flows of three lotus root cultivation modes in Wanqingsha, Nansha District, Guangzhou, China were examined using Energy Systems Language models and emergy evaluation to better understand their ecological and economic characteristics on multiple spatial and temporal scales. The natural resource foundations, economic characteristics and sustainability of these modes were evaluated and compared. The results showed that although all three modes were highly dependent on purchased emergy inputs, their potential impacts as measured by the local (ELR_L) and global (ELR_W) environmental loading ratios were less than 1.2 and 0.7, respectively. The lotus-fish mode was the most sustainable with its emergy index of sustainable development (EISD) 2.09 and 2.13 times that of the pure lotus and lotus-shrimp modes, respectively. All three lotus-root production modes had superior economic viability, since their Output/Input ratio ranged from 2.56 to 4.95. The results indicated that agricultural systems may have different environmental impacts and sustainability characteristics at different spatial and temporal scales, and that these impacts and characteristics can be simultaneously explored using integrated emergy and economic evaluations.

1. Introduction

Lotus (*Neumbo nucifera*, Gaertn) is a perennial hydrophyte with a beautiful flower and an edible root that grows indigenously in Southeast Asia. The planting and consumption of lotus root in China has a history of over 3000 years (Yang, 2007; Li et al., 2007). Currently, lotus is the most important aquatic vegetable in China, with an area of about 133,000 ha in cultivation. Furthermore, the market demand for lotus root has continued to improve, since increasing attention has been paid to the lotus root for its nutritive value and its functions in health care (Zhang et al., 2006; Yang, 2007). Consequently, some further development of lotus root production modes has occurred, but progress has been slow, due to the low growth efficiency and low economic benefits obtained from growing lotus root, compared with other land uses in the region (Xue et al., 2006; Zheng, 2010; Zhou, 2010). To fill this gap, a suite of new production modes have been developed in a series of breeding and ecological engineering studies (Ao et al., 2005; Tan et al., 2006; Cao et al., 2007; Yang, 2007; Yao et al., 2012). However, the integrated ecological economic effects of these modes have not been studied, even though this knowledge is essential for optimizing agricultural production and carrying out strategic planning in the region.

Wanqingsha is located on reclaimed wetlands around the estuary of the Pearl River, and it is famous for the production of a local lotus breed, Xinken lotus root. In 2009, the Chinese government designated Wanqingsha as the primary agricultural conservation area for Xinken lotus root (Wu et al., 2011; Zhang et al., 2016). Local

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governments and farmers want to further develop the production of this breed by trying new agro-ecological, engineering modes, e.g., lotus-fish and lotus-shrimp culture, for the purpose of attaining greater economic benefit for the farmers and for cultural conservation of Xinken lotus farming. What are the ecological-economic characteristics of these new modes for lotus root production? Could the application of these new modes improve the ecological-economic viability of the production system for lotus root? Are these new lotus root production systems competitive with nearby farms carrying out other agricultural activities? All these questions need to be answered to guide the formulation of future conservation and production strategies, and they are the topics considered in this study.

Both economic and ecological issues need to be considered, under the need to seek sustainable development at all scales, which is clearly a problem beyond the ability of pure economic or environmental analysis. Energy Systems Theory (Odum, 1983) and the emergy evaluation methods (Odum, 1996) provide a solution for this problem that is based on a biophysical theory of donor value, hierarchy theory, and self-organization under the maximum empower principle (Odum, 1996). Emergy was defined as the available energy of one type previously used up directly or indirectly in the production process of a product or service (Odum, 1996). Emergy methods take the energetic contributions of ecosystems and the biosphere into account in all ecological-economic analyses, which is essential to understand ecological engineering processes like agricultural production, but is missed in classical economic analyses (Odum, 1988, 1996; Campbell, 2001; Lan et al., 2002; Odum, 2007). The above characteristics of emergy have made emergy evaluation a reliable tool for considering the long-term and large scale sustainability of a system (Brown et al., 2000, 2003, 2005, 2007, 2009, 2011, 2013, 2015). In the past two decades, emergy evaluation has been widely applied in agricultural systems on different scales as illustrated by studies from many nations (Ulgiati et al., 1993; Lan et al., 1998; Odum, 2004; Chen et al., 2006; Jiang et al., 2007); states and provinces (Lin et al., 2013; Yi and Xiang, 2016; Cheng et al., 2017; Wang et al., 2017; Zhai et al., 2017); cities and regions (Lu et al., 2009; Chen and Chen, 2012, 2014) and specific farms (Bastianoni et al., 2001; Cavalett et al., 2006; Lu et al., 2006; Castellini et al., 2006; Pizzigallo et al., 2008; Vassallo et al., 2009; Xi and Qin, 2009; Li et al., 2011; Zeng et al., 2013; Merlin and Boileau, 2017). In contrast to 'utility value', i.e. receiver value which has a regional and short term characteristic, emergy provides a 'donor value', based on the biophysical inputs to a process converted to emergy which change slowly on the scale of global processes and long-term evolution following the maximum empower principle (Odum, 2007). Consequently different results for systems have been found when comparing the emergy and economic evaluations (Cai et al., 2005; Bastianoni et al., 2007). What is needed to guide decision-making and policy implementation is holistic assessment of the maximum ecological and economic benefits obtained on both the regional and short term scale, as well as the global and long-term scale. Integrated economic and emergy evaluations can fill this need. To accomplish this end, increasing attention has been paid to the comparison and integration of emergy and economic analyses (Lu and Campbell, 2009; de Barros et al., 2009; Lu et al., 2009, 2010, 2014; Zeng et al., 2013). However, a unified integration method combining emergy and economic evaluation methods is still under development. A "state of the art" integration of emergy and economic methods was applied in this study to evaluate and compare the viability of three different lotus root production modes at both regional and short-term, as well as, global and long-term scales. A suite of emergy-based ratios were calculated specifically to explore the environmental and sustainability impacts on the system at different spatial and temporal scales. Furthermore, a comparison was made between the lotus root production systems and other nearby farms carrying out agricultural activities typical for the region, i.e. crops and fruit production (Lu et al., 2010), aquaculture (Li et al., 2011) and eco-tourist farms (Wang et al., 2008).

2. Study site and methods

2.1. Study site

Wanqingsha is located on the estuary of the main branch of the Pearl River (22°26′N–22°44′N, 113°13′E–113°43′E, Fig. 1). It is a peninsula that was formed by natural deposition and inning, which started over 200 years ago, and its land area has now increased to 319.2 km^2. Wanqingsha is controlled by a subtropical ocean climate, and therefore, it does not have a cold winter, or a hot summer. Its annual average temperature is 21.8 °C. The area receives an annual average precipitation of 1.635 m, and the annual solar radiation is above 5E+09J/m^2 (Lu et al., 2009). With flat land, fertile soil and a well-developed stream network, Wanqingsha has been developed as an essential agricultural and aquaculture area in the skirt of Guangzhou city, one of the three largest metropolises in China. For a long time, Wanqingsha has been famous for its fruit, lotus root and pond fish production. In recent years, the land used for planting Xinken lotus root has remained around 1300ha or 20% of Wanqingsha's total plantation area. The study site, Fenglian farm (22°36′55.47″-22°37′36.32″N and 113°35′21.13″-113°36′05.41″E, Fig. 1), is the largest farm growing lotus root in Guangdong Province. It is a 120ha demonstrational plantation for Xinken lotus root composed of 18 lotus ponds, i.e., an average of 6.67ha/pond. Most of the farm's products were exported to the USA, Canada, Europe and Southeast Asia. Among the 18 lotus ponds in cultivation, six were used for the lotus-shrimp mode of production, one for the lotus-fish mode, and the other 11 for pure lotus root production. To leave some habitat for shrimp and fish, the planting density of lotus root of the lotus-shrimp and lotus-fish mode was 81% and 72% that of the pure lotus mode. The specific areas and production programs of the three lotus root production modes are given in Table 1.

2.2. Methods

The economic inputs to and outputs from the three modes of production were recorded over the course of one year with the cooperation of Fenglian farm. A conceptual energy systems language diagram (Odum, 1983) of the three lotus root production modes was drawn to clarify both the composition and interactions of flows within the systems and across system boundaries (Fig. 2). Then, all energy, material and monetary flows were converted into emergy through multiplication by the appropriate Unit Emergy Values (UEVs) and placed in emergy synthesis tables (Appendix, Table A, B, C), where they were further classified and summed up following the commonly used emergy evaluation programs (Lu et al., 2009; 2010; 2014, Fig. 2). Furthermore, to integrate emergy and economic evaluation, the emergy buying power of the monetary flows paid for purchased inputs (M_I) and the emergy received in the money paid for economic outputs (M_Y) were also quantified (Lu et al., 2010, Fig. 2). All the inputs of lotus root for vegetative reproduction, juvenile shrimp and fish fry were taken as purchased nonrenewable resources (F_{NC}), because they were all purchased from highly industrialized nursery systems and also improved the processing capacity of the systems under study (Lu et al., 2014). Ninety percent of the emergy input required for labor was assumed to be F_{NC}, considering that the renewable emergy fraction of the Chinese economy had already decreased to 11.9% in 2005 (Yang

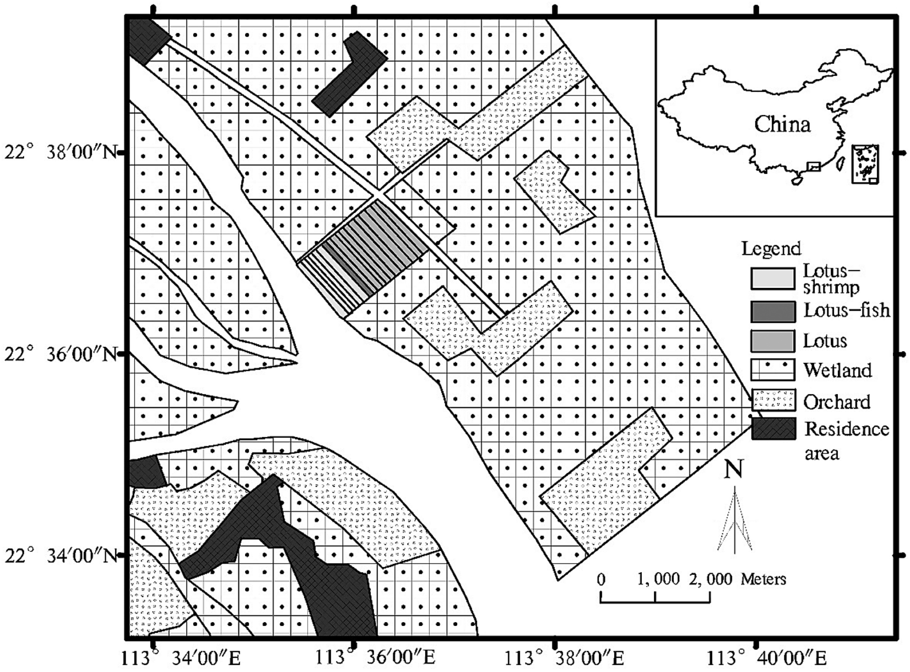

Fig. 1. Location of the study sites of three lotus root production modes.

Table 1
Characteristics and production processes of the three lotus-root production modes.

Item	Pure Lotus root	Lotus root-shrimp	Lotus root-fish
Area (ha)	73.37	40.02	6.67
Planting time and density	The end of March and the middle of August, *Neumbo nucifera* 10.77t/ha	The end of March and the middle of August, *Neumbo nucifera* 8.74t/ha	The end of March and the middle of August, *Neumbo nucifera* 7.80t/ha
Harvesting time and yield	The end of July and February of next year, 37.5t/ha	The end of July and February of next year, 37.5t/ha	The end of July and February of next year, 37.5t/ha
Input of juvenile shrimp and fry		The end of August, *Metapenaens affinis* 204000 ind./ha	The end of August, *Oreochromis spp* 4200ind./ha, *Aristichthys nobilis* 3000 ind./ha, *Channa argus* 1500ind./ha
Harvest time and yield of fish and shrimp		March of next year, 0.61t/ha	March of next year, 9.45t/ha

et al., 2010). Organic fertilizer and herbal medicine (tea bran) were taken as purchased resources, which would cause environmental load elsewhere (F_{NR}), if not being recycled to the lotus farm. Specifically, they were purchased from local animal breeding farms and tea oil factories, where they are by-products that would need extra treatment to meet environmental standards, if not being sold to other users.

In addition to the analysis of the composition of the inputs and outputs, a suite of emergy indices (Table 2) were calculated to explore the ecological economic characteristics of the three modes of lotus production, in terms of their self-sufficiency (Emergy Self-sufficiency Ratio, ESR), production efficiency (Emergy Yield Ratio, EYR), environmental impact (Environmental Loading Ratio, ELR), long-term sustainability (Emergy Sustainability Index, ESI), trading fairness for inputs (Emergy Exchange Ratio for inputs, EER_I) and for yields (EER_Y), and the temporal feasibility of sustainable development (Emergy Index for Sustainable Development, EISD) etc.

Furthermore, based on the above classification of inputs, the environmental impact of the lotus cultivation systems under study were characterized into local and global aspects of the impact, i.e., Environmental Loading Ratios for the local vicinity of the farm and for the whole regional/global system (ELR_L and ELR_W) were quantified, following the strategy of Lu et al. (2014). The modified version of the ELR proposed by Ortega et al. (2002) was also calculated, and named as ELR* to evaluate sustainability instead of environmental loading by considering the renewability of each of the economic resources used but not the pressure on the processing capacity of local environment. ELR_L is equal to the ratio of the local loading elements to the purchased and free inputs thought to increase environmental processing capacity, whereas ELR_W is the environmental loading of the whole regional/global system, with its natural processing capacity assumed to be equal to R of the local system. The purchased inputs, F_{NR}, i.e. organic fertilizer and tea bran, were components of the numerator for ELR_L, because both inputs added to the load on the processing capacity of the local system. However, for ELR_W, they did not contribute to the load on the environment of the larger system, since they were removed from that system by recycling them for use in lotus production (Table 2). Consequently, the sustainability indices, ESI, EISD, ESI_L, $EISD_L$, ESI_W, and $EISD_W$ were calculated. As mentioned earlier, Ortega's formulation, which emphasizes sustainability by placing all renewable resources in the denominator of the expression, gives an inverse measure of sustainability. Considering that ELR* is actually an indicator of sustainability itself (Lu et al., 2014), it is not used for further calculation of ESI and EISD, which are also measures of sustainability. In addition to emergy evaluation, a simple economic analysis that calculated economic viability (the economic output/input ratio, O/I, dimensionless) and land use efficiency (net

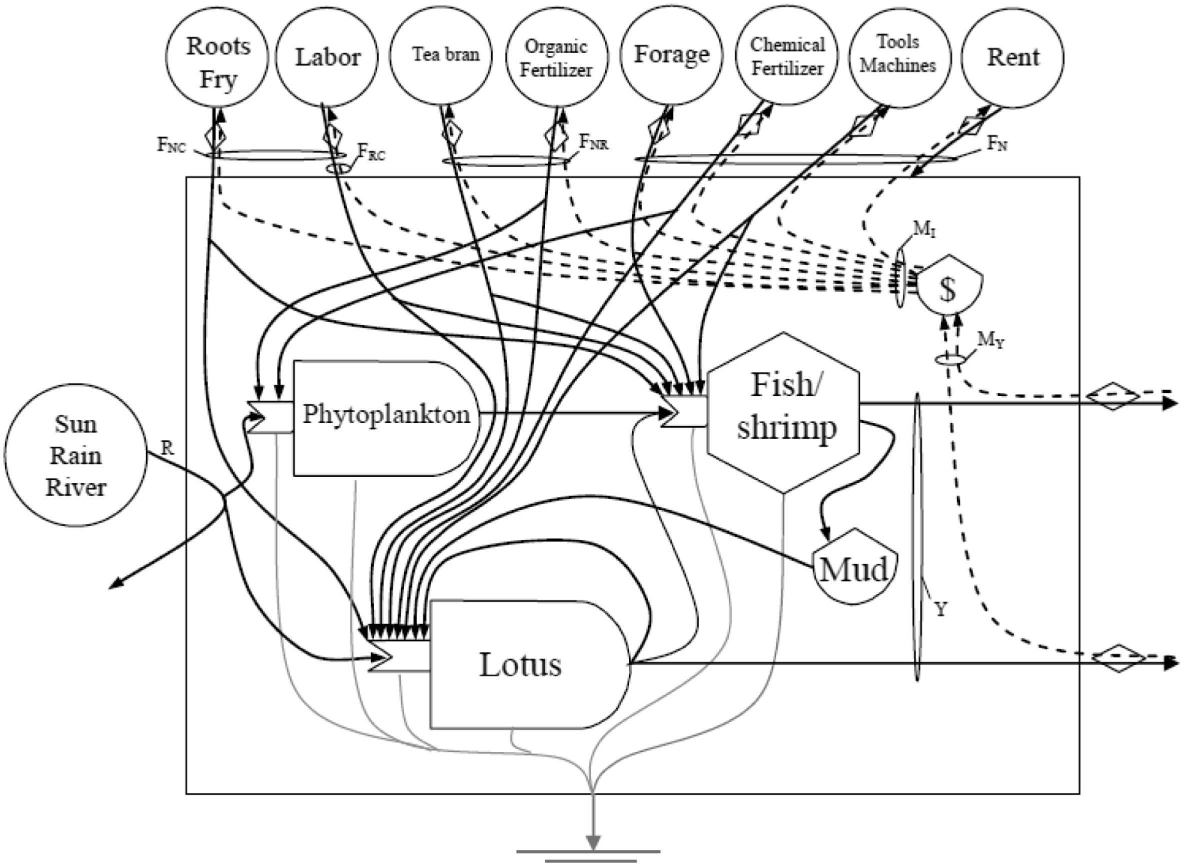

Fig. 2. Conceptual emergy systems diagram of the lotus-fish/shrimp production system. ▭ System frame ○→ Source ⊃ Producer ⬡ Consumer ⬡ Storage tank ⊳ Interaction ◇ Exchange ⟶ Emergy flow - - -▶ Money flow ⏚ Heat sink, the dispersal of available energy; R – Renewable local natural resources; F_{RC} – Purchased renewable resources which can improve the processing capacity; F_{NC} – Purchased nonrenewable resources which can improve the processing capacity; F_N – Purchased resources causing environmental load, locally and elsewhere; F_{NR} – Purchased resources which would cause environmental load elsewhere if not being recycled; Y – Yield, equal to the total emergy input for production systems under steady state; M_I – Buying power of the money spend for the purchased inputs; M_Y – Buying power of the money received for sale of the yield from the system.

benefits density, NBD, $/ha) were also performed, and integrated with the emergy evaluation results to allow a more complete exploration of the ecological-economic characteristics of the three lotus production modes.

To make consistent comparisons with other emergy evaluation studies in the same area (Lu et al., 2009, 2010), the 9.26E+24 seJ/yr planetary baseline (Campbell, 2000) was applied in this study. All the results of this study can be easily converted to the latest planetary emergy baseline, 12E+24 seJ/yr (Brown et al., 2016), by multiplying 1.296.

3. Results

3.1. Emergy evaluation results

3.1.1. Input composition

All three lotus root cultivation modes depended on purchased emergy for over 95% of their inputs. Although over 94% of the total emergy input to all three modes was purchased non-renewable resources, over 40% of these resources (lotus root, fish fry and juvenile shrimp) enhanced the processing capacity of the system

Table 2
Emergy indices employed in this study and their equations.

Index	Equation	Source
Emergy Self-sufficiency Ratio (ESR)	$ESR = (R + N)/U$	Odum, 1996
Environmental Loading Ratio (ELR)	$ELR = (N + F_N + F_{NC} + F_{NR} + F_{RC})/R$	Odum, 1996
Environmental Loading Ratio* (ELR*)	$ELR^* = (N + F_N + F_{NC})/(R + F_{RC} + F_{NR})$	Ortega et al., 2002
Environmental Loading Ratio for the local system (ELR_L)	$ELR_L = (N + F_N + F_{NR})/(R + F_{RC} + F_{NC})$	Lu et al., 2014
Environmental Loading Ratio for the global system (ELR_W)	$ELR_W = (N + F_N)/(R + F_{RC} + F_{NC})$	Lu et al., 2014
Emergy Yield Ratio (EYR)	$EYR = Y/F$	Odum, 1996
Emergy Sustainability Index (ESI)	$ESI = EYR/ELR$	Brown and Ulgiati, 1996
Emergy Sustainability Index for the local system (ESI_L)	$ESI_L = EYR/ELR_L$	Lu et al., 2014
Emergy Sustainability Index for the global system (ESI_W)	$ESI_W = EYR/ELR_W$	Lu et al., 2014
Emergy Exchange Ratio for Inputs (EER_I)	$EER_I = U/(M_{FN} + M_{FNC} + M_{FNR} + M_{FRC})$	Lu et al., 2010
Emergy Exchange Ratio for Outputs (EER_Y)	$EER_Y = Y_M/Y$	Lu et al., 2010
Emergy Exchange Ratio (EER')	$EER' = (F_N + F_R + Y_M)/(M_{FN} + M_{FR} + Y)$	Lu et al., 2010
Emergy Index for Sustainable Development (EISD)	$EISD = EYR^*EER/ELR$	Lu et al., 2002
EISD for the local system ($EISD_L$)	$EISD_L = EYR^*EER/ELR_L$	Lu et al., 2014
EISD for the global system ($EISD_W$)	$EISD_W = EYR^*EER/ELR_W$	Lu et al., 2014

under study (F_{NC}). Another large fraction of the nonrenewable inputs (F_{NR}), accounting for over 20% of total F, was contributed by recycled materials (i.e., organic fertilizer and tea bran), that would have been pollutants, if they had been allowed to remain in their production systems located in the region. Thus, less than 25% of the nonrenewable input was classified as F_N, which is the usual classification of purchased inputs (Fig. 3a). Lotus root constituted a fraction of the inputs to all three production modes that was higher than 30%. Thus, it was the largest emergy input to all lotus cultivation modes, followed by organic fertilizer, chemical fertilizer, rent and labor, in that order (Fig. 3b).

Detailed analysis of the composition of inputs showed that the addition of fish aquaculture to the lotus pond was accompanied by a 36% and a 32% increase in labor and chemical fertilizer inputs, respectively; but no forage input was required (Appendix Tables B and C). To give fish some habitat space, the planting density of lotus root was decreased to 72% that of the pure lotus root mode. In addition, the emergy input in the fish fry was 2 orders of magnitude lower than that of lotus root; thus, the empower density of the lotus-fish mode was 0.93 times that of the pure lotus mode. The emergy input of juvenile shrimp to the lotus-shrimp mode is much higher than that of fish fry (7.69% vs. 0.71%), and the lotus root input was decreased by 18%, accompanied by a 32% increase in labor and a 13% increase in chemical fertilizer compared to the pure lotus production mode (Appendix, Tables A, B and C). Finally, the lotus-shrimp mode had the highest empower density (7.37E+16 sej/ha/yr), followed by the pure lotus cultivation mode (6.90E+16 sej/ha/yr), leaving the lotus-fish mode with the lowest empower density (6.42E+16 sej/ha/yr, Table 3).

3.1.2. *Emergy indices*

Since all three production modes were highly dependent on purchased emergy inputs, the emergy self-sufficiency ratio (ESR) of all three was lower than 0.05, with that of the lotus-shrimp mode being the lowest (0.038, Table 4). The classic environmental loading ratios (ELR) of all three modes were higher than 22 due to the high fraction of purchased emergy input. However, classification of purchased input flows according to their capacity to increase or decrease load on the environment indicated a low environmental loading for the three modes, with all ELR_L and ELR_W less than 1.2

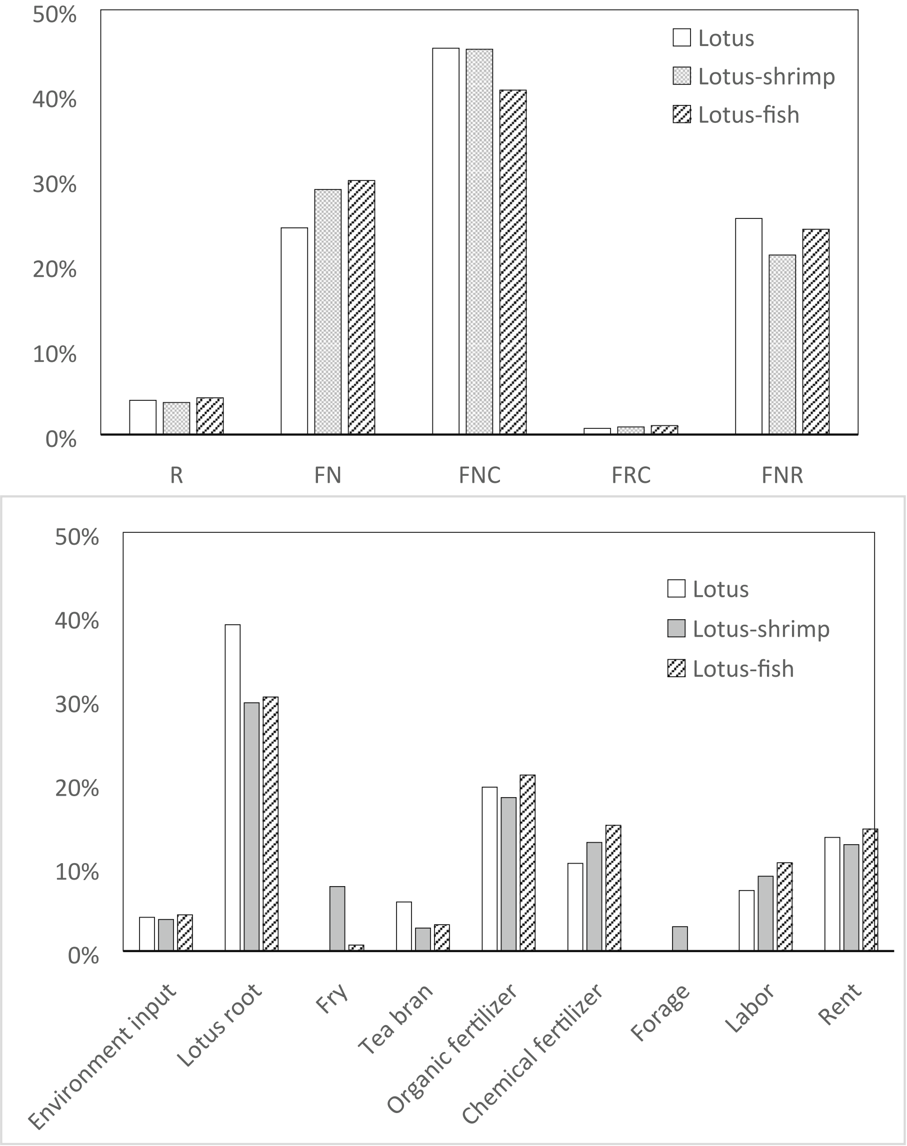

Fig. 3. Composition of the emergy inputs to the three lotus root production modes. a) Aggregate composition of emergy inputs to the three modes. b) Detailed fractions of the emergy inputs to the three modes.

and 0.7, respectively. All the ELR^* values were less than 2.9 indicating moderate sustainability. The ESI indicated that the lotus-fish mode was the most sustainable followed by the pure lotus and then the lotus-shrimp modes. However, ESI_L and ESI_W indicated that the pure lotus mode had the highest sustainability for both the local and global systems, followed by the lotus-shrimp and then the lotus-fish modes. The ELR^* also indicated that pure lotus was the most sustainable mode, but it was followed by the lotus-fish, and then the lotus-shrimp modes.

All three production modes under study obtained extra benefit from market exchange with the emergy exchange ratios for both input (EER_I) and output (EER_Y) greater than 1. The EER_{Ys} of all three modes were especially favorable, being higher than 2.2 in all cases, which means the emergy buying power of the money received as a reward for their outputs, i.e. lotus root, shrimp and fish, was over 2 times the emergy required to produce the outputs (Table 4). The lotus-fish mode had an EER_Y (4.27) that was, respectively, 1.89 and 1.69 times higher than that of the pure lotus and lotus-shrimp modes, which made its emergy index of sustainable development (EISD) 2.09 and 2.13 times that of the pure lotus and the lotus-shrimp modes, respectively. The EER of the lotus-shrimp mode is 5% higher than that of the pure lotus mode, which is not large enough to change the order of its sustainability among the three modes over either the short-term or the long-term as measured by EISD and $EISD_W$, respectively. However, the EER does make a difference in sustainability at the local scale ($EISD_L$), at which we found the lotus-shrimp mode's sustainability to be higher than that of the pure lotus mode. Finally, overall, the emergy indices showed that the lotus-fish mode was the most sustainable of the 3 modes studied.

For general economic production systems that have not been optimized by competition in long-term evolution, the transformities and specific emergies of their products can be used to measure the relative efficiencies of the production processes. The lower the transformity or specific emergy for the same product, the higher the efficiency of the production system for that product (Lu et al., 2010). Among the three modes examined, the lotus-fish mode had the lowest transformity and specific emergy; and therefore, it was the most efficient system for lotus root production. This index was 0.96 and 0.83 times that of the lotus-shrimp and pure lotus modes, respectively (Table 5). The transformity and specific emergy of fish from the lotus-fish mode, which lacked forage inputs, was only 3% that of the shrimp from the lotus-shrimp mode. Furthermore, this difference was also caused by the fact that the productivity of fish (9450 kg/ha/yr) was over 15 times the productivity of shrimp (613.65 kg/ha/yr) (Table 5).

3.2. Economic analysis

Over 93% of economic costs for the three modes was spend on purchasing non-renewable resources (Fig. 4a). The cost of lotus root for regeneration was the largest fraction (over 32% of economic costs for all three modes), followed by labor, land rent and organic fertilizer (Fig. 4b). The different order of the emergy and economic inputs showed that the system exploited the relatively low price of organic fertilizer compared to the high market price of labor. Since we did not know the unit emergy value (UEV) of lotus root before this study, its market value was used for the input accounting, and the input of lotus root for regeneration was consequently taken as a purchased non-renewable input. However, from the emergy evaluation, in this study, we can see that the current market price was between 2.26 and 2.74 times the emergy-money (Em¥) values of lotus root (Appendix Tables A, B, and C). Considering the vegetative reproduction method of lotus root cultivation, we suggest that the farmers keep part of their yield for the next season's regeneration, for both economic and environmental reasons.

Table 3
Aggregated emergy (empower density) inputs to and output from the three lotus root production systems (sej/ha/yr).

Item	Lotus	Lotus-shrimp	Lotus-fish
R	2.78E+15	2.78E+15	2.78E+15
F_N	1.68E+16	2.13E+16	1.92E+16
F_{NC}	3.14E+16	3.34E+16	2.60E+16
F_{NR}	1.75E+16	1.56E+16	1.55E+16
F_{RC}	5.00E+14	6.59E+14	6.79E+14
U	6.90E+16	7.37E+16	6.42E+16
M_I	6.10E+16	6.92E+16	5.53E+16
Y	6.90E+16	7.37E+16	6.42E+16
M_Y	1.56E+17	1.87E+17	2.74E+17

Table 4
Emergy indices of the three lotus root production modes.

Index	Lotus	Lotus-shrimp	Lotus-fish
ESR	0.040	0.038	0.043
ELR	23.825	25.528	22.116
ELR^*	2.313	2.876	2.384
ELR_L	0.991	0.999	1.177
ELR_W	0.484	0.577	0.651
EYR	1.042	1.039	1.045
ESI	0.044	0.041	0.047
ESI_L	1.052	1.040	0.888
ESI_W	2.151	1.802	1.605
EER_I	1.131	1.065	1.161
EER_Y	2.262	2.532	4.265
EER'	2.558	2.696	4.954
EISD	0.112	0.110	0.234
$EISD_L$	2.690	2.804	4.398
$EISD_W$	5.502	4.859	7.952

The brief economic analysis showed that the lotus-fish mode was the best production choice, since it had both the highest economic O/I ratio (4.954) and NBD (262,568.85¥/ha/yr, Table 6). It was followed by the economic indicators of the lotus-shrimp mode. As the last economic choice among the three modes under study, both the economic O/I ratio and NBD of the pure lotus mode were still high at 2.558 and 114,213.75¥/ha/yr, which showed the general superior economic characteristics of lotus root production.

4. Discussion

Lotus-aquaculture is not a new cultivation mode in China, but the fact that it is ecologically and economically superior was not widely noticed until a suite of reports published in 1980s (Li, 1986; Chen et al., 2003). After that, many studies have been done on specific lotus production technologies accompanied by brief economic analyses. These studies have been based on ecological theory and some assumptions about the operation of food-chains, which indicated that the addition of aquaculture would benefit the cultivation of lotus root. The mechanism for improved production is based on the fact that fish can feed on some aquatic grasses that compete with lotus for habitat and resources. Also, fish feed on pests that can injure the lotus, and they improve the dissolved

Table 5
Transformities and specific emergies of the products from the three lotus root production systems.

Product	Transformity	Specific emergy
	sej/J	sej/g
Lotus root (from the pure lotus mode)	6.27E+05	1.84E+09
Lotus root (from the lotus-shrimp mode)	5.38E+05	1.58E+09
Lotus root (from the lotus-fish mode)	5.18E+05	1.52E+09
Shrimp	5.89E+06	2.37E+10
Fish	1.78E+05	7.74E+08

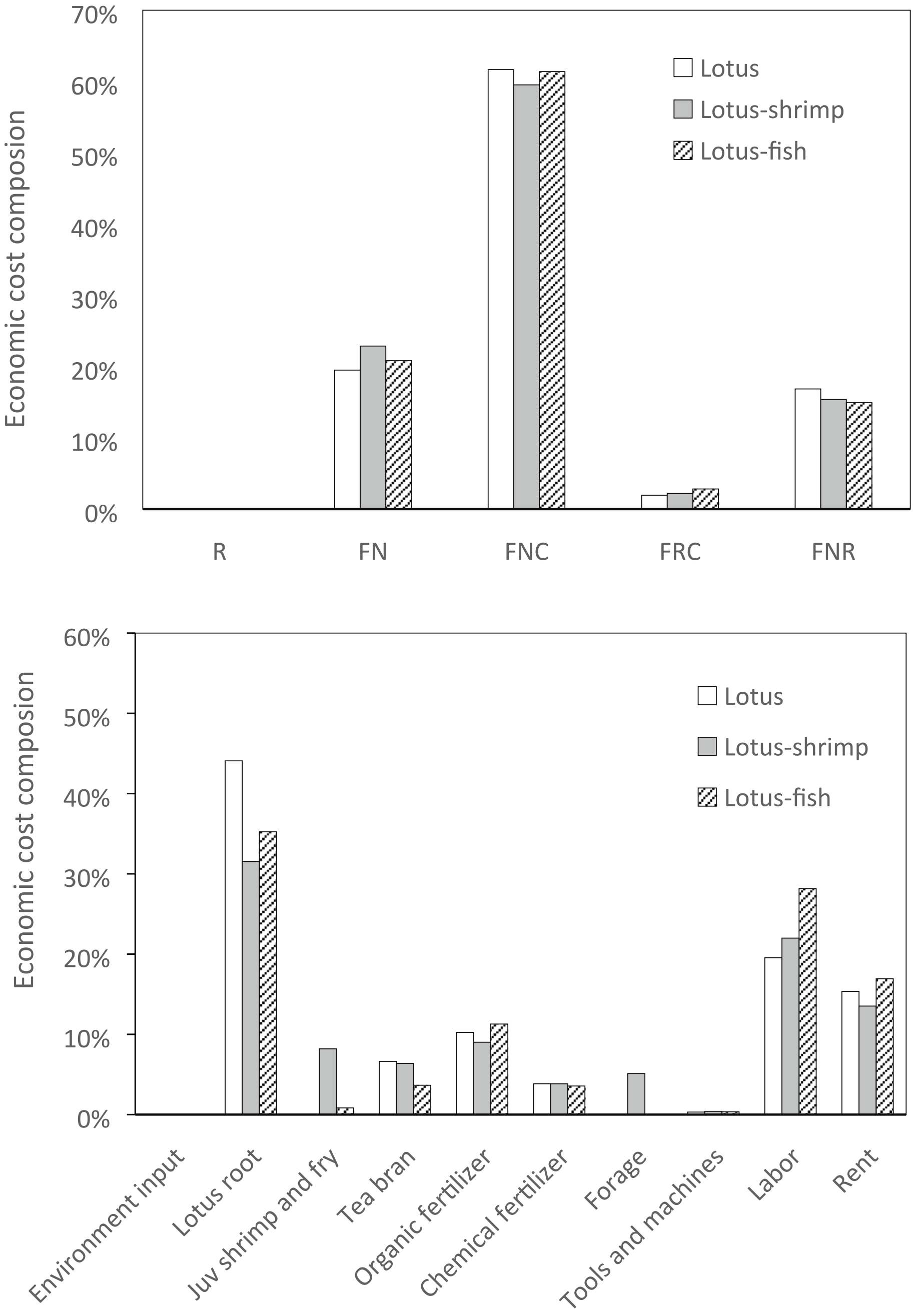

Fig. 4. Composition of economic investment into the three lotus root production systems. a) Aggregate composition of economic inputs to the three modes. b) Detailed fractions of the economic inputs to the three modes.

oxygen (DO) content in pond water by swimming and burrowing activities, and provide fertilizing excreta to the mud that enhances lotus growth (Long, 1997; Ao et al., 2005; Yu, 2007; Wang, 2006; Zheng, 2006; Wu, 2006). These mechanisms showing how the addition of shrimp and fish enhance lotus growth may partly explain why the productivity of all the three lotus root production modes is same in this study. However, further specific cultivation studies are needed to optimize the planting density for all the three modes. The brief economic analysis that we found in literature explored the economic O/I ratio of the lotus-fish modes at other places, which ranged from 1.8 to 2.8, with the net benefit density (NBD) varying from 11,625 to 140,550 ¥/ha/yr (Huang, 2004; Ao et al., 2006; Wang et al., 2007; Yuan, 2008; Mao et al., 2015).

Compared with the above results, the three modes under study, especially the lotus-fish mode, had both high economic O/I ratios (from 2.56 to 4.95) and NBD (from 114,213 to 262,788 ¥/ha/yr). No integrated ecological economic evaluations of lotus cultivation or lotus-aquaculture systems were found in literature to be used here for comparison to our results. The intra-comparison of modes in this study showed the addition of aquaculture subsystems to the lotus pond did improve the production efficiency of lotus root. This fact is evidenced by a decrease in the UEV of the lotus root produced and an increase in the economic O/I ratio and NBD of the system as a whole. However, these improvements also had a tradeoff in terms of increased environmental impact, as shown by the increase of ELR_L and ELR_W. Thus, the loadings to both the local and global systems increased, and consequently sustainability decreased as shown by the decrease in ESI_L and ESI_W. Combining

Table 6
Aggregated economic flows and indices of the three lotus root production systems.

Item	Lotus	Lotus-shrimp	Lotus-fish
Aggregated flows (¥/ha/yr)			
Renewable Natural Resources	0	0	0
Lotus roots input	32305.05	26243.55	23419.50
Fry	0	6818.25	552
Organic fertilizer	7500	7500	7500
Tea bran	4860	5298.75	2430
Chemical fertilizer	2816.4	3193.2	2367.6
Forage	0	4254.6	0
Tools and machines	229.8	339	229.8
Labor	14325	18293.25	18713.25
Rent	11250	11250	11250
Total Input	73286.25	83190.60	66462.15
Market Value of Outputs	187500	224318.25	329250
Economic Indices			
Output/input ratio (O/I)	2.558	2.696	4.954
Net Benefit Density (NBD, ¥/ha/yr)	114213.75	141127.65	262787.85

the emergy and economic evaluation results, we can see that both the density of aquaculture and the aquatic species selection can affect the final ecological-economic effects on the system as a whole. The addition of aquatic species with a suitable niche and relatively high market price (high EER_Y) in low density seems to be the right direction to increase ecological and economic benefits.

All the lotus roots used for vegetative reproduction in the three modes under study were purchased from outside the farm. In terms of environmental loading, lotus root was classified as a purchased non-renewable input without performing detailed tracing studies, which would clearly overestimate the environmental impact to some degree. From the detailed emergy analysis we can see that the renewable fraction (R%) of the inputs (without accounting for the input of lotus roots) to the pure lotus root cultivation mode was 7.8%. On the output side, the EER for lotus root produced by the pure lotus root cultivation mode was high (2.26), and lotus root purchased for vegetative reproduction accounts for 44% of the total economic cost. Thus, using self-produced lotus root for starting next season's crop maybe more economic for the cultivation system, as well as having lower environmental impacts. Of all purchased inputs in this study, the renewable fraction was only considered for labor. However, the production process for each input has consumed both renewable and nonrenewable resources throughout its supply chain (Shao and Chen, 2016). Thus, the environmental loadings of the agricultural systems under study were all over estimated to some degree.

Orchards and aquaculture are two other typical farms found on reclaimed wetland surrounding the Pearl River Estuary, Wanqingsha (Lu et al., 2009; Li et al., 2011). Eco-tourist farms based on cultivation or aquaculture systems have been started in recent years in the same area (Wang et al., 2008). It is clearly essential for regional land use planning, to quantify and compare the ecological-economic characteristics of these different kinds of farms. A comparison of production modes in Wanqingsha and the surrounding area (see Tables 3 and 7) showed that the pure lotus cultivation mode had empower similar to four nearby orchards. These empower densities are higher than that of the lake with low density tourism activities, but a fraction (0.12–0.34) of the empower densities of the three aquaculture and the farmyard ecotourism systems. The pure lotus growth system had an ESI that was about the same as the nearby orchards and the aquaculture ponds. The relatively high price received for lotus root on the market made the EISD of this growth system the same as two of the three aquaculture systems and two of the orchards examined, and higher than that of the other two orchards and the farmyard tourism system, but its EISD was much lower than that of a nearby lake with low density ecotourism activities. The addition of shrimp into the lotus pond did not improve the ecological-economic characteristics of lotus culture as expected, while the addition of fish at a low density did. The ESI of the lotus-fish mode is higher than that of all 4 orchards, and its economic O/I is higher than that of all other systems examined. Finally, the lotus-fish system had the highest EISD among all the systems under comparison (Tables 4 and 7).

At present, there are about 1300 ha of lotus ponds and 839 ha of aquaculture ponds in Wanqingsha, but almost no integrated lotus-aquaculture ponds. Thus, further integration of these production modes is an important direction for optimization of the regional ecological-economic system not only for making the use of regional natural resources more efficient, but also for furthering economic development.

To maximize economic benefit and minimize the 'load' on the environment is the key target of all ecological-economic systems, under the strategy to move toward more sustainable development. Consequently, the quantification of environmental impact continues to be an important issue in emergy evaluation studies with the classic ELR (Odum, 1996; Brown and Ulgiati, 1996) as the most widely applied index, which is defined as the ratio of purchased (F) and nonrenewable indigenous emergy use (N) to free environmental emergy (R). The assumption behind ELR is that all purchased inputs are a load on local environment, which is clearly not right for all scales of evaluation (Brown et al., 2012; Lu et al., 2014). Some purchased inputs can improve the processing capacity of the system under study, e.g. lotus-root in this study, and other inputs are recycled pollutants from other systems, e.g. manure and tea bran in this study. The use of both of these functional types of inputs lead to cleaner modes of agricultural production. Taking these different functional modes into consideration, the purchased inputs were further classified, and consequently the ELR was extended to the formulations ELR_L and ELR_W (Lu et al., 2014) to explore the environmental loading at local and global scales, respectively. Compared with the ELR loading estimate, ELR_L and ELR_W showed that over 18 times less environmental load was being applied in the 3 lotus root production modes under study than would be the case

Table 7
Emergy and economic indices of some cultivation, aquaculture and eco-tourist systems on reclaimed wetland surrounding the Pearl River Estuary.

Mode		Empower (sej/ha/yr)	EYR	ELR	ESI	EER_I	EER_Y	EISD	O/I	NBD (¥/ha/yr)
Orchard[a]	Banana	3.67E+16	1.04	25.19	0.04	1.11	2.52	0.10	2.26	60234.47
	Papaya	5.81E+16	1.16	40.13	0.03	0.94	1.82	0.05	1.93	60641.24
	Guava	6.18E+16	1.31	43.22	0.04	1.13	1.98	0.06	1.76	64432.55
	Wampee	4.46E+16	1.30	30.89	0.03	1.32	4.87	0.20	3.69	157358.83
Aquaculture[b]	Eel	2.14E+17	1.04	23.42	0.05	0.61	2.59	0.11	4.09	668076.00
	Ophicephalus	2.37E+17	1.05	20.18	0.05	1.04	2.69	0.13	2.47	456643.00
	Weever	3.04E+17	1.04	26.15	0.04	1.48	2.99	0.11	1.95	489455.00
Eco-tourist[c]	Luhua Lake	2.33E+16	1.02	13.92	0.07	1.48	2.57	0.20	1.83	41634.42
	Farmyard	1.40E+17	1.01	91.82	0.01	1.08	3.56	0.04	3.31	559206.67

[a] Lu et al., 2009.
[b] Li et al., 2011.
[c] Wang et al., 2008.

if the functional properties of the inputs were not considered. Thus, this study quantified the environmental benefits of ecological engineering (including agricultural engineering) to attain cleaner agricultural production processes through the application of inputs that improve the processing capacity of the local environment and by recycling potential pollutants that would have to be processed as wastes elsewhere, as inputs to support agricultural production.

5. Conclusion

1) The lotus-fish mode of production was the most sustainable among the three modes under study, as shown by the fact that it had the highest emergy yield ratio (EYR) and the lowest environmental loading ratio (ELR). Furthermore, the lotus-fish mode also had the highest economic viability, since it had both the highest economic O/I ratio and NBD. Finally, the integrated emergy and economic evaluation showed that the lotus-fish mode was the best option for both long-term sustainable operation of lotus root production and was compatibility with present ecological economic characteristics of the system, i.e., it had the highest emergy index for sustainable development (EISD).
2) The three lotus production modes had much higher economic viability than reported for lotus cultivation systems at other places in China, and compete well for land use with nearby orchards, aquaculture ponds and eco-tourist systems established on reclaimed wetland surrounding the Pearl River Estuary. Considering the potential eco-tourism value of lotus ponds, which was not counted in this study, the promotion of lotus cultivation is recommended as a strategy for furthering regional development.
3) Agricultural systems may have different environmental impacts and sustainability characteristics at different spatial and temporal scales, which need to be holistically considered in decision-making and planning. Integrated emergy and economic evaluation is a valuable tool to accomplish this end.
4) Characterizing the inputs to production systems according to their functional role in determining the environmental load caused by a production process, increases our understanding of environmental loads at different spatial and temporal scales and provides a way to move toward cleaner production processes.

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Appendix

Table A
Emergy analysis table of the pure lotus root growth mode (/ha/yr).

Item	Raw data	Transformity (sej/unit)	Solar emergy (sej)	Em-money value (Em¥)	Market value (¥)
Renewable Nature Resources (R)					
Solar radiation	4.70E+13 J	1.00E+00[a]	4.70E+13	56.4	
Wind	7.89E+08 J	1.47E+03[b]	1.16E+12	1.35	
Rain (Geo-potential)	1.48E+09 J	1.03E+04 [b]	1.53E+13	18.3	
Rain (Chemical)	7.71E+10 J	1.81E+04 [b]	1.40E+15	1678.05	
Earth cycle	1.45E+10 J	3.37E+04 [b]	4.89E+14	588.45	
River water (Chemical)	2.76E+10 J	5.01E+04 [b]	1.38E+15	1660.35	
Subtotal R			2.78E+15	3338.4	
Purchased Non-renewable Resources (F_N)					
Rent	1.13E+04 yuan	8.32E+11 [c]	9.36E+15	11250	11250
Wood boat	9.75E+04 J	7.75E+04 [b]	7.56E+09	0	208.35
Pump	25.80 kg	7.76E+12 [b]	2.01E+14	241.05	19.95
Shovel	0.30 kg	7.76E+12 [b]	2.43E+12	2.85	1.5
Nitrogen fertilizer	2340 kg	2.99E+12 [b]	7.01E+15	8414.25	2348.4
Compound fertilizer	75.30 kg	2.99E+12 [b]	2.25E+14	270.6	468
Subtotal F_N			1.68E+16	20178.75	14296.20
Purchased Non-renewable Resources enhancing processing capacity (F_{NC})					
Lotus root input	3.23E+04 yuan	8.32E+11 [c]	2.69E+16	32305.05	32305.05
Labor	2.64E+09 J	1.70E+06 [d]	4.49E+15	5399.25	12892.5
Subtotal F_{NC}			3.13E+16	37704.30	45197.55
Purchased Non-renewable Resources decreasing regional loading (F_{NR})					
Organic fertilizer	18750 kg	7.20E+11 [e]	1.35E+16	16221.9	7500
Tea bran	4860 yuan	8.32E+11 [c]	4.04E+15	4860	4860
Subtotal F_{NR}			1.75E+16	21081.90	12360
Purchased Renewable Resources enhancing processing capacity (F_{RC})					
Labor	2.94E+08 J	1.70E+06 [d]	5.00E+14	599.85	1432.5
Subtotal F_{RC}			5.00E+14	599.85	1432.5
Total input			6.8E+16	82903.5	73286.25
Yield					
+	37500 kg	1.84E+12	6.90E+16	82903.5	187500
	1.10E+11 J[f]	*6.27E+05*			

[a] Odum (1996).
[b] Campbell et al. (2005).
[c] Li et al. (2011).
[d] Lan et al. (1998). Converted to 9.26E+24sej/yr baseline from 9.44E+24sej/yr.
[e] Cavalett et al. (2006). Converted to 9.26E+24sej/yr baseline from 15.83E+24sej/yr.
[f] Energy content of every gram was cited from: http://www.fumuqin.com/View.aspx?id=4749.

Table B
Emergy analysis table of the lotus-shrimp mode (/ha/yr).

Item	Raw data	Transformity (sej/unit)	Solar emergy (sej)	Em-money value (Em¥)	Market value (¥)
Renewable Nature Resources (R)					
Solar radiation	4.70E+13 J	1.00E+00 [a]	4.70E+13	56.4	
Wind	7.89E+08 J	1.47E+03 [b]	1.16E+12	1.35	
Rain (Geopotential)	1.48E+09 J	1.03E+04 [b]	1.53E+13	18.3	
Rain (Chemical)	7.71E+10 J	1.81E+04 [b]	1.40E+15	1678.05	
Earth cycle	1.45E+10 J	3.37E+04 [b]	4.89E+14	588.45	
River water (Chemical)	2.76E+10 J	5.01E+04 [b]	1.38E+15	1660.35	
Subtotal R			2.78E+15	3338.4	
[f]To Lotus (R_A)			1.39E+15	1669.2	
[f]To Shrimp (R_B)			1.39E+15	1669.2	
Purchased Non-renewable Resources (F_N)					
[f]To Lotus (F_{NA})					
Rent	5625.00 yuan	8.32E+11 [c]	4.68E+15	5625	5625
Wood boat	9.75E+04 J	7.75E+04 [b]	7.56E+09	0	208.35
Pump	25.80 kg	7.76E+12 [b]	2.01E+14	241.05	19.95
Shovel	0.30 kg	7.76E+12 [b]	2.43E+12	2.85	1.5
Nitrogen fertilizer	3045.0 kg	2.99E+12 [b]	9.11E+15	10949.25	2713.2
Compound fertilizer	150.00 kg	2.99E+12 [b]	4.49E+14	539.25	480
Subtotal (F_{NA})			1.44E+16		50252.55
[f]To Shrimp (F_{NB})					
Rent	5625.00 yuan	8.32E+11 [c]	4.68E+15	5625	5625
Wood boat	6.38E+04 J	7.75E+04 [b]	4.95E+09	0	54.6
Shrimp cage	2.28E+07 J	4.32E+04 [b]	9.84E+11	1.2	54.6
Forage	1636.35 kg	1.31E+12 [b]	2.15E+15	2577.6	4254.6
Subtotal (F_{NB})			6.83E+15	8203.80	9988.80
Subtotal ($F_N = F_{NA} + F_{NB}$)			2.13E+16	25561.20	19036.80
Purchased Non-renewable Resources enhancing processing capacity (F_{NC})					
[f]To Lotus (F_{NCA})					
Lotus root input	26243.55 yuan	8.32E+11 [c]	2.19E+16	26243.55	26243.55
Labor	3.17E+09 J	1.70E+06 [d]	5.39E+15	6472.8	14961
Subtotal (F_{NCA})			2.73E+16	32716.35	41204.55
[f]To Lotus (F_{NCB})					
Fry	6818.25 yuan	8.32E+11 [c]	5.67E+15	6818.25	6818.25
Labor	3.18E+08 J	1.70E+06 [d]	5.42E+14	650.25	1503
Subtotal (F_{NCB})		6.21E+15	7468.50	8321.25	
Subtotal ($F_{NC} = F_{NCA} + F_{NCB}$)		3.35E+16	40184.85	49525.80	
Purchased Non-renewable Resources decreasing regional loading (F_{NR})					
[f]To Lotus (F_{NRA})					
Organic fertilizer	18750 kg	7.20E+11 [e]	1.35E+16	16221.9	7500
Tea bran	2430 yuan	8.32E+11 [c]	2.03E+15	2430	2430
Subtotal (F_{NRA})			1.55E+16	18651.90	9930
[f]To Shrimp (F_{NRB})					
Tea bran	337.5 kg	1.59E+11 [c]	5.37E+13	64.5	2868.75
Subtotal (F_{NRB})		5.37E+13	64.5	2868.75	
Subtotal ($F_{NR} = F_{NRA} + F_{NRB}$)		1.56E+16	18716.40	12798.75	
Purchased Renewable Resources enhancing processing capacity (F_{RC})					
[f]To Lotus (F_{RCA})					
Labor	3.53E+08 J	1.70E+06 [d]	5.99E+14	719.25	1662.3
Subtotal (F_{RCA})			5.99E+14	719.25	1662.3
[f]To Shrimp (F_{RCB})					
Labor	3.54E+07 J	1.70E+06 [d]	6.02E+13	72.3	166.95
Subtotal (F_{RCB})			6.02E+13	72.3	166.95
Subtotal ($F_{RC} = F_{RCA} + F_{RCB}$)		6.59E+14	791.55	1829.25	
Total input ($U = R + F_N + F_{NC} + F_{NR} + F_{RC}$)		7.38E+16	88592.40	83190.60	
Total input to Lotus ($U_A = R + F_{1A} + R_{1A}$)		5.92E+16	71114.10	61844.85	
Total input to Shrimp ($U_B = R_B + F_{1B} + R_{1B}$)		1.45E+16	17478.30	21345.75	
Yield (Y)					
Lotus root (Y_A)	37500 kg	*1.58E+12*	5.92E+16	71114.25	187500
	1.10E+11 J	*5.38E+05*			
Shrimp (Y_B)	613.65 kg	*2.37E+13*	1.45E+16	17478.3	36818.25
	2.46E+09 J	*5.89E+06*			

** Energy content of every gram was cited from: http://www.fumuqin.com/view.aspx?id=5386.

[a] Odum (1996).

[b] Campbell et al. (2005).

[c] Li et al. (2011).

[d] Lan et al. (1998). Converted to 9.26E+24sej/yr baseline from 9.44E+24sej/yr.

[e] Cavalett et al. (2006). Converted to 9.26E+24sej/yr baseline from 15.83E+24sej/yr.

[f] Energy content of every gram was cited from: http://www.fumuqin.com/View.aspx?id=4749.

Table C
Emergy analysis table of the lotus-fish mode (/ha/yr).

Item	Raw data	Transformity (sej/unit)	Solar emergy (sej)	Em-money value (Em¥)	Market value (¥)
Renewable Nature Resources (R)					
Solar radiation	4.70E+13 J	1.00E+00 [a]	4.70E+13	56.4	
Wind	7.89E+08 J	1.47E+03 [b]	1.16E+12	1.35	
Rain (Geopotential)	1.48E+09 J	1.03E+04 [b]	1.53E+13	18.3	
Rain (Chemical)	7.71E+10 J	1.81E+04 [b]	1.40E+15	1678.05	
Earth cycle	1.45E+10 J	3.37E+04 [b]	4.89E+14	588.45	
River water (Chemical)	2.76E+10 J	5.01E+04 [b]	1.38E+15	1660.35	
Subtotal			2.78E+15	3338.4	
[f]To Lotus (R_A)			1.39E+15	1669.2	
[f]To Fish (R_B)			1.39E+15	1669.2	
Purchased Non-renewable Resources (F_N)					
[f]**To Lotus (F_{NA})**					
Rent	5625 yuan	8.32E+11	4.68E+15	5625	5625
Wood boat	9.83E+04 J	7.75E+04	7.62E+09		126.9
Pump	25.80 kg	7.76E+12	2.01E+14	241.05	19.95
Shovel	0.30 kg	7.76E+12	2.43E+12	2.85	1.5
Nitrogen fertilizer	3210 kg	2.99E+12	9.60E+15	11542.5	2319.6
Compound fertilizer	15 kg	2.99E+12	4.49E+13	54	48
Subtotal (F_{NA})			3.95E+16	47357.1	8140.95
[f]**To fish (F_{NB})**					
Rent	5625 yuan	8.32E+11 [c]	4.68E+15	5625	5625
Wood boat	6.30E+04 J	7.75E+04 [b]	4.89E+09	0	81.45
Subtotal (F_{NB})			4.68E+15	5625.0	5706.45
Subtotal ($F_N = F_{NA} + F_{NB}$)		1.92E+16	52982.10	13847.40	
Purchased Non-renewable Resources enhancing processing capacity (F_{NC})					
[f]**To Lotus (F_{NCA})**					
Lotus root	23419.50 yuan	8.32E+11 [c]	1.95E+16	23419.5	23419.5
Labor	3.17E+09 J	1.70E+06 [d]	5.39E+15	6472.2	14861.1
Subtotal (F_{NCA})			2.49E+16	29891.70	38280.60
[f]**To Lotus (F_{NCB})**					
Fry	552 yuan	8.32E+11 [c]	4.59E+14	552	552
Labor	4.20E+08 J	1.70E+06 [d]	7.14E+14	858.3	1970.85
Subtotal (F_{NCB})			1.17E+15	1410.30	2522.85
Subtotal ($F_{NC} = F_{NCA} + F_{NCB}$)			2.61E+16	31302.00	40803.45
Purchased Non-renewable Resources decreasing regional loading (F_{NR})					
[f]**To Lotus (F_{NRA})**					
Organic fertilizer	18750 kg	7.20E+11 [e]	1.35E+16	16221.9	7500
Tea bran	2430 yuan	8.32E+11 [c]	2.03E+15	2430	2430
Subtotal (F_{NRA})			1.55E+16	18651.90	9930
Subtotal (F_{NR})			1.55E+16	18651.90	9930
Purchased Renewable Resources (F_{RC})					
[f]**To Lotus (F_{RCA})**					
Labor	3.53E+08 J	1.70E+06 [d]	5.99E+14	719.25	1662.3
Subtotal (F_{RCA})			5.99E+14	719.25	1662.3
[f] **To Fish (F_{RCB})**					
Labor	4.67E+07 J	1.70E+06 [d]	7.94E+13	95.4	219
Subtotal (F_{RCB})			7.94E+13	95.4	219
Subtotal ($F_{RC} = F_{RCA} + F_{RCB}$)		6.78E+14	814.65	1881.30	
Total input ($U = R + F_N + F_{NC} + F_{NR} + F_{RC}$)		6.42E+16	107089.05	66462.15	
Total input to Lotus ($U = R_A + F_{NA} + F_{NCA} + F_{NRA} + F_{RCA}$)		3.79E+15	5.69E+16	68397.45	
Total input to Fish ($U = R_B + F_{NB} + F_{NCB} + F_{NRB} + F_{RCB}$)		4.88E+14	7.32E+15	8799.9	
Yield (Y)					
Lotus root (Y_A)	37500 kg	*1.52E+12*	5.69E+16	68397.45	187500
	1.10E+119 J[f]	*5.18E+05*			
Fish (Y_B)	9450 kg	*7.74E+11*	7.32E+15	8799.9	141750
	4.11E+10 J[g]	*1.78E+05*			

[a] Odum (1996).
[b] Campbell et al. (2005).
[c] Li et al. (2011).
[d] Lan et al. (1998). Converted to 9.26E+24sej/yr baseline from 9.44E+24sej/yr.
[e] Cavalett et al. (2006). Converted to 9.26E+24sej/yr baseline from 15.83E+24sej/yr.
[f] Energy content of every gram was cited from: http://www.fumuqin.com/View.aspx?id=4749.
[g] Energy content of every gram was cited from: http://www.fumuqin.com/view.aspx?id=5461.

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