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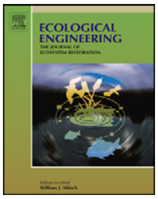

Emergy and economic evaluations of four fruit production systems on reclaimed wetlands surrounding the Pearl River Estuary, China

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ABSTRACT

Emergy and economic methods were used to evaluate and compare a traditional tropical fruit cultivation system, for bananas, and three newly introduced fruit cultivation systems, for papaya, guava and wampee, on reclaimed wetlands of the Pearl River Estuary, China. The goal of this study was to apply ecological engineering principles to fruit production system designs to maximize total emergy benefits and sustainability. The evaluations considered input structure, production efficiency, environmental impacts, economic viability and sustainability. The market effects on emergy exchange were assessed both for purchasing the inputs to production and for selling the fruit. These market effects were also considered in the evaluation of sustainability by using the Emergy Index for Sustainable Development (EISD), which was evaluated with and without taking the change in natural capital (i.e., soil organic matter) into consideration. The results showed that all three of the newly introduced systems are much more sustainable than the traditional banana production system. The guava production system had the highest value of the Emergy Sustainability Index (ESI = 0.40). The high price of wampee gave it the highest economic yield/cost ratio (4.87) and EISD (0.73). Emergy and economic evaluations are complementary methods, with emergy analysis shedding more light on environmental support and impacts of the production systems not considered in the market value, and economic analysis focusing on the effects of markets on fruit production. The Emergy Exchange Ratio (EER) was proposed as a bridge between emergy and economic evaluations for specific systems and/or processes.

1. Introduction

An estuary is the water body connecting freshwater and saltwater; not only is it the terminus of the watershed, but also it is the beginning of the ocean. It is a center for the convergence of natural energy, e.g., waves, tides, river water, and material flows, such as the sediments from uplands, and it has high primary productivity, biodiversity, and rich deposits of alluvium (Lu, 2003; Zhuang, 2008). The high renewable empower density found there is an attractor for social and economic development with concomitant high population density and tough land use competition (Qin et al., 2004) that accompanies rapid development. The intense competition for land in the rapidly developing area around the Pearl River Estuary has resulted in reclaiming many wetland areas surrounding the estuary for agriculture. With sustainable development as the goal, the question "How can we protect highly desirable coastal areas and also allow appropriate development to occur?" has become one of the most difficult issues confronting not only local, regional and national governments but also land owners and the public. An objective, quantitative evaluation of the advantages and disadvantages of current and classical land use patterns surrounding estuaries is an essential first step in solving this problem.

The wetland surrounding the Pearl River Estuary is one of the largest estuarine wetlands in the world, with an area of 1,864,101 ha (Peng and Wang, 2004). It is contained within the Pearl River Delta, an area of rich alluvial soil. Large areas of this wetland have been reclaimed and farming is one of the main long-term land uses found there (Peng and Wang, 2004; Chen et al., 2005). In 2004, there were 36,585 ha of farmland on former wetland reclaimed from the estuary (Wang, 2005). The government released its price controls on fruit in 1983, after which the food consumption patterns of local people changed, so that the economic benefits

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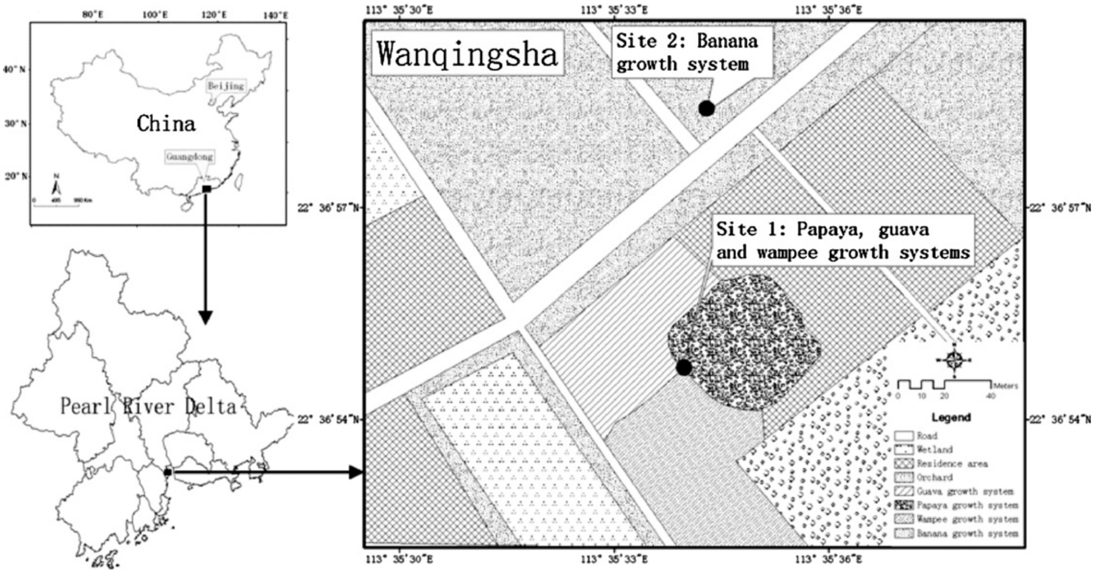


Fig. 1. Location of Wanqingsha and study sites of the four fruit production systems.

gained from fruit growing improved quickly. Consequently, the area planted in fruit trees increased dramatically, and fruit growing became the main agricultural activity in this area. In addition to traditional banana culture, recently some new fruit species (e.g., papaya, guava and wampee) have been successfully introduced to the area. Cultivation of these species increased rapidly after their introduction, due to the high economic benefit gained from them. A quantitative, ecological–economic evaluation of the advantages and disadvantages of the traditional and new fruit culture systems was needed for land use planning to promote sustainable development of this area and for improving emergy and economic benefits of the fruit production system designs though the application of ecological engineering principles.

Advances in Energy Systems Theory (Odum, 1983) and environmental accounting (Odum, 1996) developed the theory and methods for using emergy to evaluate different energy, material and money flows in terms of their equivalent ability to do work in a network. The method uses emergy per unit values, i.e., transformity, specific emergy and the emergy to money ratio, to convert energy, material, and monetary measures of all kinds to solar emjoules allowing direct comparison, addition, and subtraction of formerly disparate quantities; thereby, successfully filling in the blanks for the environmental contributions to economic production formerly missing from economic evaluations (Odum, 1988, 1996, 2007; Lan et al., 2002). After nearly 20 years of development and application, emergy synthesis has become a more common and tested evaluation method for ecological economic systems and processes (Brown et al., 2000, 2003, 2005, 2007), and it has been successfully applied in evaluations of wetlands and agricultural systems (Ton et al., 1998; An et al., 1998; Rydbergy and Jansén, 2002; Arias and Brown, 2009; Campbell et al., 2009). Three parts of the method are of particular interest in this paper.

First, the calculation and accumulation of new transformities and specific emergies is of interest. Transformity is defined as the quantity of one kind of energy used directly or indirectly to make a unit of another kind of energy. Transformity measures the position of an item in the universal hierarchical system of energy transformations. It shows the relative production efficiency of systems and processes and along with other emergy per unit values (e.g., the specific emergy), it serves as the means for converting different kinds of energy and matter to emergy units, in this case solar emjoules (sej). The calculation and documentation of transformities and specific emergies through the evaluation of production processes is a fundamental requirement for further development and application of emergy synthesis methods (Odum, 1996). For fruits, this work has just started, and only a few calculations have been done on the production of oranges (*Citurs aurantium*) and watermelons (*Citrullus lanatus*) in Florida, US (Brandt-Williams, 2002), red oranges in Italy (La Rosa et al., 2008), grapes (*Vitis vinifera*) in Italy (Bastianoni et al., 2001) bananas (*Musa paradisiaca*) in Guadeloupe, French West Indies (De Barros et al., 2009), blackberry (*Rubus fruticosus*) in Ohio, US, and papaya (*Carica papaya*) in Mexico (Martin et al., 2006). No emergy analyses, transformities, or specific emergies have been published for guava (*Psidium guajava*) or wampee (*Clausena lansium*).

Second, the fact that emergy analysis is often performed on systems not at steady state is of interest. Soil nutrients are often not in steady state in crop production systems and they are clearly the most important storage needed for fruit cultivation. Although they are often depleted, they can also increase as a consequence of the cultivation method used. The fundamental tool of Energy Systems Theory for investigating systems not in steady state is model building and dynamic simulation. We did not simulate models of the fruit production systems; however, we did measure and evaluate changes in the soil organic matter during the fruit production process to provide essential information on the maximization of ecological–economic benefits for land use planning with the goal of sustainable development in mind.

Third, the relationship between, emergy and economic analysis methods and their potential integration are of interest. Emergy methods have been called “a bridge between environment and economy” (Lan et al., 2002). This ability to synthesize measures of ecological and economic assets is becoming more widely recognized, and some of the emergy evaluation predictions have proved to be correct (Campbell, 2001; Odum, 2004). The application of emergy analysis in real production and management systems is still rather limited as a result of the difficulty of fully integrating emergy analysis results with the results of economic analysis (Campbell and Cai, 2007), and by the fact that the latter approach is currently the dominant value measurement system in the world.

Where do these differences come from? Could emergy accounting and economic analysis become an integrated system of valuation, more accurately measuring the values contributed by environmental and economic processes? And if they could, how can this end be accomplished? All of these questions need further study.

In this study that is based on a one-year investigation, both emergy and economic analysis methods were applied to evaluate four fruit production systems occupying reclaimed wetland around the Pearl River Estuary. The results of studying the structure of inputs and the efficiency of production using the two methods were compared. A bridge between emergy and economic analysis is provided by the Emergy Exchange Ratio (EER) (Odum, 1996), which was applied to analyze both the output from and inputs to each production system. This analysis shed some light on the reasons for differences between the methods, and allowed us to explore a possible direction for integrating the two methods. The evaluation results were considered with and without taking the change of soil organic matter into consideration.

2. Location and study sites

Located near the estuary of the main branch of the Pearl River (22°26′N–22°44′N, 113°13′E–113°43′E, Fig. 1), Wanqingsha is the biggest farming area among the five main farming areas on former wetland surrounding the Pearl River estuary. These areas are Jipuosha, Wanqingsha, Hengmen, Jinxing and Humen (Liu et al., 1998). Wanqingsha is controlled by a subtropical ocean climate and it has an annual average temperature of 21.8 °C. The area receives an annual average rainfall of 1.635 m, and the annual solar radiation is above 5E+09 J/m^2 (Ge et al., 1997; PYCEC, 1994, www.gzwqs.gov.cn at June 23, 2008).

The land occupied by Wanqingsha came from natural deposition and inning, which began over 200 years ago. With flat land, fertile soil and a well developed stream network, Wanqingsha developed as an essential area of agriculture and aquaculture at the outskirts of Guangzhou City, and it is known for its banana, lotus and fish production. Currently, there are about 5333 ha used for agriculture in Wanqingsha. Among them, about 3000 ha are used to grow bananas, with an annual output of 120,000 t. The planting of large areas of Wanqingsha in bananas brought dramatic economic benefits to local farmers, but also some difficulties, i.e., pest management and disease control. For example, Panama disease (*Fusarium wilt*) has caused serious damage and a rapid decline in the area dedicated to banana production in recent years. Simultaneously, local markets have developed for other fresh fruits. Because of these problems, a 15.33 ha fruit research center was built in Wanqingsha by the Guangzhou Fruit Sciences Institute in January, 2003, for testing and encouraging the production of new fruit species, such as papaya, guava and wampee. In 2006, the area of papaya and guava under cultivation in Wanqingsha had expanded to over 530 ha of papaya and 200 ha of guava. Many farmers are interested in growing these new fruit species, because of the high economic benefits they can obtain. Under the requirement for regional sustainable development (Guangzhou Agenda 21 Leader Group Office, 1998), an urgent question is, “Are the production systems for these new fruit species superior to the traditional banana planting system, when environmental impacts are included in the accounting?”

Experimental plots for papaya (6.67 ha), guava (4.67 ha) and wampee (1.47 ha) in the fruit research center of the Guangzhou Fruit Sciences Institute at Wanqingsha (22°36′56″N, 113°35′35″E), and a 1.33 ha plot of bananas 50 m away were selected as the study sites for a one year investigation (Fig. 1). From 2006 to 2007, measurements were made and sampling was performed with the cooperation of the farmers working in the land.

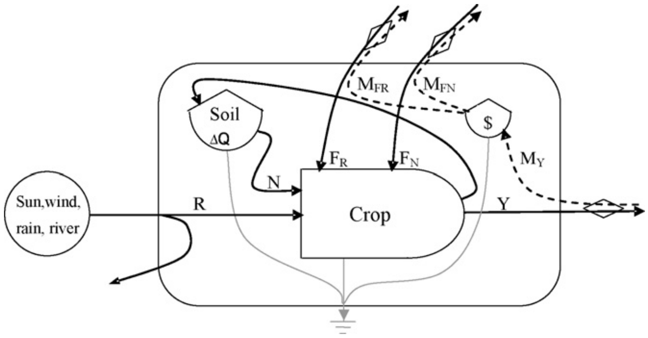


Fig. 2. The general emergy system diagram of a planting system.

3. Methods

In January 2006 and January 2007, three 2-cm cores for the measurement of soil density and organic matter content were randomly collected from each system using a 3-cm diameter coring tube. From January 2006 to January 2007, three samples of the stream water used for irrigation were collected from each system every two months and the concentration of total dissolved solids (TDS) was measured. The long-term annual mean climate data, for solar radiation, rainfall and wind, were taken from the Wanqingsha government weather station. The quantity and prices of inputs to and output from the fruit production systems were determined with the help of the farmers working at the fruit production systems.

Following a general system diagram of a fruit crop production system (Fig. 2), the inputs and outputs were converted into emergy units based on the 9.26E24 sej/yr planetary baseline (Campbell, 2000), using transformities, specific emergies and emergy to money ratios available in the literature. All transformities found in the literature were converted to this baseline before comparison with our results. Inputs were aggregated into local renewable resources (R), local nonrenewable resources (N), purchased nonrenewable resources (F_N) and purchased renewable resources (F_R), for analysis of the production structures and calculation of indices. To avoid double counting, only the chemical potential energy of rain and river water entering from outside the system were added to estimate the total R, since the chemical potential energy of rain was the largest one among the renewable emergy co-products of the solar emergy basis for the earth.

Since all of the seedlings came from professional nurseries, which were highly dependent on machines and fossil fuels, they were classified as F_N. Ninety percent of the labor input was classified as F_N, while the other 10% went into F_R, following the results in Uligati et al. (1994). The loss of soil organic matter was counted as a local nonrenewable input, while an increase in soil organic matter was counted as a co-product with the fruit output, and consequently was given the same emergy required for the fruit.

Emergy indices were calculated to measure the structure of the inputs, the efficiency of production, the environmental impact, the fairness of market exchange, the ecological economic benefits gained, and the sustainability of the systems under study. The formulations for indices used in this study are shown in Table 1.

The Ecological Benefit in Exchange (EBE) index developed by Lu et al. (2007) was revised so that it now has a parallel structure with that of the EER. This change allows the EBE to show the balance between the total economic-ecological products benefiting the larger system and the emergy purchasing power of the money flows received in compensation for all system outputs (Table 1). In addition, the ESI formulation was extended from EYR/ELR to produce a new formulation EBR/ELR, which provides an index that takes the change of internal ecological capital into account

Table 1
Existing and revised emergy indices used in this study.

Index	Formulation	Utility	Reference
Empower density (EPD)	U/area	An indicator for the intensity of emergy flows and development in space	Odum (1996)
Emergy Self-Sufficiency Ratio (ESR)	$(R+N)/U$	An indicator giving the fraction of emergy used that comes from within the system	Odum (1996)
Environmental Loading Ratio (ELR)	$(N+F_N)/(R+F_R)$	An indicator of the potential pressure on local ecosystems, or the ecosystem stress due to production activity	Odum (1996), Lu et al. (2002)
Emergy Yield Ratio (EYR)	$Y/(F_R+F_N)$	An indicator of the ability of the larger system/process to exploit local resources.	Odum (1996)
Emergy Exchange Ratio (EER)	Y_M/Y	An indicator for the emergy benefits gained from the sale of products	Odum (1996)
Emergy Sustainability Index (ESI)	EYR/ELR	An indicator of system sustainability, the ratio of emergy yield to environmental load	Brown and Ulgiati (1997)
Emergy Index for Sustainable Development (EISD)	EYR × EER/ELR	An indicator for the sustainability of the system, considering the effects of market exchange on the emergy yield	Lu et al. (2003)
Emergy Benefit Ratio (EBR)	$(Y+\Delta Q)/(F_R+F_N)$	An indicator of the emergy yield as a function of feedback from the economy that considers both the change in internal ecological capital and the emergy yield to the larger system	Lu et al. (2007)
Emergy Benefit in exchange (EBE)	$(Y_M+\Delta Q_M)/(Y+\Delta Q)$	An indicator of the ecological economic state of the system as determined by market exchange	Revised from the EBE in Lu et al. (2006, 2007)
ESI after considering the change of storage ($\text{ESI}_{\Delta Q}$)	EBR/ELR	An indicator of system sustainability considering both the change in internal ecological capital and the emergy yield to the larger system	Extended from the ESI in Brown and Ulgiati (1997)
EISD after considering the change of storage ($\text{EISD}_{\Delta Q}$)	EBR × EBE/ELR	An indicator of system sustainability considering both ecological and economic affects on the emergy yield	Lu et al. (2006, 2007)

in assessing sustainability. This modified measure of sustainability was named as $\text{ESI}_{\Delta Q}$, where ΔQ represents any increase in natural capital storages within the system.

The EER has been widely used to measure the effects of market exchange on the emergy balance between the buyer and the seller, when system outputs are sold on the market. In addition, for this study, we also calculated the Emergy Exchange Ratio for purchased inputs. We believe that both inputs and outputs must be considered for a holistic analysis of market effects on any system under study. To avoid confusion, here we call the EER of the output EER_Y, and the EER for the purchased input EER_I. Since the system under study is the consumer of purchased inputs, the function for EER_I is F/F_M, or $(F_N+F_R)/(F_{NM}+F_{RM})$, if the purchased sources were classified into nonrenewable (F_N) and renewable (F_R) inputs. An EER_I less than 1 means the system under study lost emergy during the purchasing of its input, and *vice versa*, an EER_I greater than 1 reveals that the system under study obtained extra real wealth in purchased inputs over the real wealth (emergy) that ordinarily could be purchased with the money paid for them.

The EER_I was also introduced into the calculation of the Emergy Index for Sustainable Development (EISD) both without and with the consideration of changes in internal storages ($\text{EISD}_{\Delta Q}$). The EISD calculations were compared with similar calculations of the Emergy Sustainability Index (ESI) both without and with the consideration of any increase in internal natural capital storages ($\text{ESI}_{\Delta Q}$). This comparison demonstrates the market effects on the sustainability of the systems under study. To represent the economic output/input ratio, the product of the Emergy Yield Ratio (EYR) and the EER of both output and input ($\text{EYR} \times \text{EER}_\text{Y} \times \text{EER}_\text{I}$) was also calculated (see Section 5).

Transformity is one of the main concepts of Energy Systems Theory and Emergy Synthesis methods, because it provides information on both the position of an item in the energy hierarchy and the efficiency with which the item is produced. Assuming that the accumulation of soil organic carbon (SOC) is a co-product with fruit production, the total emergy used in the system ($U=R+N+F_R+F_N$) was assigned to the increment in SOC, as well as to the fruits. Consequently, the transformity and specific emergy of the fruits and the increment of SOC were calculated by dividing the emergy required for the production system by the energy content and the weight of fruit and the increment of SOC, respectively. This is perhaps reasonable because banana litter fall and the returning of tree prunings are by far the greatest contributors to the increase in soil organic matter (Luo and Peng, 1996).

Following the standard methods of emergy analysis (Odum, 1996), an Energy Systems Language diagram of a generic fruit production system (Fig. 2) was constructed, detailed emergy analysis tables were setup and calculations were performed for each system under study (Tables 2–5). A column of market values for each item was added to the standard emergy analysis tables for use in comparing the results of emergy and economic measures of value.

4. Results

4.1. Emergy accounting

On the basis of detailed emergy analyses of the fruit production systems (Tables 2–5), aggregated emergy flows and a suite of emergy indices were calculated (Table 6). Two bar charts show the results of our analysis of the structure of the inputs to production at both the aggregated (Fig. 3a) and detailed (Fig. 3b) levels. The solar transformities and specific emergies of the products are given in Table 7 and compared with those of fruit and soil organic matter determined from other systems.

Table 2
Emergy and economic analysis table for the banana production system (flows/ha/yr).

Item	Raw data	Transformity (sej/unit)	Solar emergy (sej)	Em-value (EM¥)	Market value (¥)
Local renewable resource input (*R*)					
Solar radiation	4.70E+13 J	1.00E+00[a]	4.70E+13	56.45	
Wind	7.89E+08 J	1.47E+03[b]	1.16E+12	1.39	
Rain (geopotential)	1.48E+09 J	1.03E+04[b]	1.52E+13	18.34	
Rain (chemical)	7.71E+10 J	1.81E+04[b]	1.40E+15	1678.03	
Earth cycle	1.45E+10 J	3.37E+04[b]	4.89E+14	588.39	
River water	8.75E+07 J	5.01E+04[b]	4.38E+12	5.27	
Subtotal			1.40E+15	1683.30	
Purchased nonrenewable input (F_N)					
Rent	7050 ¥	8.32E+11[c]	5.86E+15	7050.00	7050.00
Labor (90%)	3.91E+09 J	1.70E+06[d]	6.64E+15	7987.43	6783.75
Pump	29.06 kg	7.76E+12[b]	2.26E+14	271.18	1800.00
Sprayer	2.81 kg	7.76E+12[b]	2.18E+13	26.24	600
Plastic bag	82.50 kg	1.87E+12[e]	1.54E+14	185.69	495
Plastic rope	450 ¥	8.32E+11[c]	3.74E+14	450.00	450.00
Diesel oil	392.06 kg	2.82E+12[a]	1.11E+15	1329.45	1568.25
Gas	33.3 kg	2.82E+12[a]	6.39E+13	112.92	136.53
Chemical fertilizer	4537.50 kg	2.99E+12[b]	1.36E+16	16313.75	9776.25
Chemical pesticide	5502 ¥	8.32E+11[c]	4.58E+15	5502.00	5502.00
Seedlings	2475 ¥	8.32E+11[c]	2.06E+15	2475.00	2475.00
Subtotal			3.47E+16	41703.67	36636.78
Purchased renewable input (F_R)					
Labor (10%)	4.34E+08 J	1.70E+06[d]	7.38E+14	887.49	753.75
Bamboo	2.76E+10 J	4.32E+04[a]	1.19E+15	1431.36	2200.00
Subtotal			1.93E+15	2318.86	2953.75
Total input (*U*)			3.80E+16	45705.82	39590.53
Yield					
Banana	45375 kg 1.73E+11 J[f]	*8.38E+11** *2.20E+05***	3.80E+16	45705.82	99825
Soil organic matter	1.82E+11 J	*2.09E+05*	3.80E+16	45705.82	

[a] Odum (1996).
[b] Campbell et al. (2005).
[c] http://sahel.ees.ufl.edu/database_resources.php?search_type=basic&country=CHN, the emergy/US$ in China in 2000, converted to 9.26E24 sej/yr baseline from 15.83E24 sej/yr baseline, and the exchange ratio between RMB and US$ in 2000 is 8.3.
[d] Lan et al. (1998). Converted to 9.26 E24 sej/yr baseline from 9.44 E24 sej/yr.
[e] Brown and Bardi (2001). Converted to 9.26 E24 sej/yr baseline from 15.83 E24 sej/yr.
[f] http://www.fumuqin.com/View.aspx?id=5047.
* Transformity calculated from this study.
** Specific emergy calculated from this study.

4.1.1. *Structure of the emergy inputs*

The total input of local renewable resources to a hectare of each of the four fruit production systems was the same (Table 6), except that papaya used a little more river water for irrigation (Tables 2–5). The traditional banana production system did not deplete the local nonrenewable natural resources in the form of lost soil organic matter, while the guava production system consumed the highest amount of soil organic matter among the three newly introduced systems (2.03 and 1.48 times that of the papaya and wampee systems, respectively).

The four fruit production systems are highly dependent on economic resources, and over 70% of the total emergy used came from this source. A comparatively large labor input to the papaya production system made it the largest user of purchased nonrenewable inputs among the four systems. Guava had the largest input of purchased renewable resources, due to its large manure use, while the input of purchased renewable resources to the banana system was only 0.15, 0.19 and 0.43 times that of the guava, papaya, and wampee, respectively.

All four systems are highly dependent on purchased nonrenewable inputs, especially the banana system, which uses a large amount of chemical fertilizer, followed by the papaya system, which requires the most labor (Fig. 3a and b). About 20% of the emergy inputs to the guava and wampee systems came from local nonrenewable resources, i.e., soil organic matter, while local nonrenewable input to the papaya system was only 11.2% of total use (Fig. 3a). The guava culture system had the highest percentage of purchased renewable inputs (20%) due to its use of organic fertilizers and it was followed by the papaya, wampee and banana in order of their dependence on this input (Fig. 3a and b).

4.1.2. *Empower density (EPD)*

Since both detailed and aggregated emergy flows were calculated per hectare per year, the emergy inputs in Table 6 are equal to the empower density of the production systems in unit of sej/ha/yr. The traditional banana system had the lowest empower density; whereas, the large use of organic fertilizer gave the guava system the highest empower density among the three newly introduced species. The guava, papaya and wampee systems had 1.69, 1.58 and 1.22 times the empower density of the traditional banana system.

4.1.3. *Emergy Self-Sufficiency Ratio (ESR)*

The traditional banana system is less dependent on local environmental resources than the three newly introduced systems, mainly because it builds soil organic matter rather than consuming it. The guava system had the highest dependence on local natural resources, and thus it was the most self-sufficient system, followed by the wampee and papaya systems, all of which consumed soil organic matter.

Table 3
Emergy and economic analysis table of the papaya production system (flows/ha/yr).

Item	Raw data	Transformity (sej/unit)	Solar emergy (sej)	EM-value (EM¥)	Market value (¥)
Local renewable resource input (*R*)					
Solar radiation	4.70E+13 J	1.00E+00[a]	4.70E+13	56.45	
Wind	7.89E+08 J	1.47E+03[b]	1.16E+12	1.39	
Rain (geopotential)	1.48E+09 J	1.03E+04[b]	1.52E+13	18.34	
Rain (chemical)	7.71E+10 J	1.81E+04[b]	1.40E+15	1678.03	
Earth cycle	1.45E+10 J	3.37E+04[b]	4.89E+14	588.39	
River water	3.32E+08 J	5.01E+04[b]	1.67E+13	20.03	
Subtotal			1.41E+15	1698.06	
Local nonrenewable resource input (*N*)					
Soil organic matter	8.96E+10 J	7.26E+04[b]	6.51E+15	7822.95	
Purchased nonrenewable input (F_N)					
Rent	9900 ¥	8.32E+11[c]	8.23E+15	9900.00	9900.00
Labor (90%)	7.46E+09 J	1.70E+06[d]	1.27E+16	15259.58	12985.31
Electricity	4.64E+09 J	1.70E+06[a]	7.91E+14	950.85	371.25
Plastic bag	129 kg	1.87E+12[e]	2.41E+14	290.36	258.00
Paper bag	2.16E+07 J	5.89E+04[f]	1.27E+12	1.53	2812.50
Package box	3.99E+07 J	5.89E+04[f]	2.35E+12	2.82	2556.82
Bulldozer	1562.55 ¥	8.32E+11[c]	1.30E+15	1562.55	1562.55
Mower	351.60 g	7.76E+09[b]	2.73E+12	3.28	93.75
Pump	9082.05 g	7.76E+09[b]	7.05E+13	84.74	703.20
Truck	15624.90 g	7.76E+09[b]	1.21E+14	145.80	781.20
Diesel oil	99.61 kg	2.82E+12[a]	2.81E+14	337.77	398.44
Gas	13.88 kg	2.82E+12[a]	3.91E+13	47.05	56.89
Compound fertilizer	1812.45 kg	2.99E+12[b]	5.42E+15	6516.33	5799.84
Nitrogenous fertilizer	167.70 kg	2.99E+12[b]	5.01E+14	603.02	335.40
Phosphorus fertilizer	1290 kg	3.02E+12[i]	3.90E+15	4688.09	670.80
Chemical pesticide	90 ¥	8.32E+11[c]	7.48E+13	90.00	90.00
Seedlings	7740 ¥	8.32E+11[c]	6.44E+15	7740.00	7740.00
Subtotal			4.01E+16	48223.77	47115.95
Purchased renewable input (F_R)					
Labor (10%)	8.29E+08	1.70E+06[d]	1.41E+15	1695.51	1442.81
Manure	10320 kg	7.20E+1[g]	7.43E+15	8928.55	4128.00
Peanut bran	7740 kg	1.59E+11[h]	1.23E+15	1479.80	21672.00
Subtotal			1.01E+16	12103.86	27242.81
Total			5.81E+16	69848.64	74358.76
Yield					
Papaya	28125 kg 3.18E+10 J[j]	*2.07E+12*[*] *1.83E+06*[**]	5.81E+16	69848.64	135000.00

[a] Odum (1996).

[b] Campbell et al. (2005).

[c] http://sahel.ees.ufl.edu/database_resources.php?search_type=basic&country=CHN, the emergy/US$ in China in 2000, converted to 9.26E24 sej/yr baseline from 15.83E24 sej/yr baseline, and the exchange ratio between RMB and US$ in 2000 is 8.3.

[d] Lan et al. (1998). Converted to 9.26 E24 sej/yr baseline from 9.44 E24 sej/yr.

[e] Brown and Bardi (2001). Converted to 9.26 E24 sej/yr baseline from 15.83 E24 sej/yr.

[f] Tilley (1999). Lumber, converted to 9.26 E24 sej/yr baseline from 9.44 E24 sej/yr.

[g] Cavalett et al. (2006). Converted to 9.26 E24sej/yr baseline from 15.83 E24 sej/yr.

[h] Shen, 2001. Converted to 9.26 E24 sej/yr baseline from 9.44 E24 sej/yr.

[i] Brandt-Williams (2002). Converted to 9.26 E24 sej/yr baseline from 15.83 E24 sej/yr.

[j] http://www.fumuqin.com/View.aspx?id=5047.

[*] Transformity calculated from this study.

[**] Specific emergy calculated from this study.

4.1.4. *Emergy Yield Ratio (EYR)*

The EYRs of the three newly introduced fruit production systems are all higher than that of the traditional banana system. The large use of labor made the EYR of the papaya system lower than that of the guava and wampee systems (Tables 2–6).

4.1.5. *Environmental Loading Ratio (ELR)*

The ELRs of the systems under study were as follows: banana (10.0), wampee (6.6), papaya (4.1) and guava (3.2). The comparatively large renewable input of organic fertilizer caused the guava system to exert the lowest total pressure on the environment.

4.1.6. *Emergy Sustainability Index (ESI)*

The Emergy Sustainability Index of all four fruit production systems was lower than 0.5; both with ($ESI_{\Delta Q}$) and without (ESI) the consideration of any increases in internal natural capital storages. Among the four systems, guava had the highest sustainability (0.40) and papaya the next highest (0.29). After taking into account the effects of increases in the internal storages on sustainability, the $ESI_{\Delta Q}$ of banana production doubled from 0.10 to 0.21. From this perspective, this traditional production system was slightly more sustainable than wampee (0.20), but still less sustainable than the other two new fruit production systems.

4.1.7. *Emergy Exchange Ratio (EER)*

All the Emergy Exchange Ratios for fruit yield (EER_Y) from the production systems were higher than 1.7, thus all of the fruit production systems gained considerable emergy benefits over the cost of production from the sale of their fruit on the market. The wampee and banana systems received an emergy

Table 4
Emergy and economic analysis table of the guava production system (flows/ha/yr).

Item	Raw data	Transformity (sej/unit)	Solar emergy (sej)	EM-value (EM¥)	Market value (¥)
Local renewable resource input (*R*)					
Solar radiation	4.70E+13 J	1.00E+00[a]	4.70E+13	56.45	
Wind	7.89E+08 J	1.47E+03[b]	1.16E+12	1.39	
Rain (geopotential)	1.48E+09 J	1.03E+04[b]	1.52E+13	18.34	
Rain (chemical)	7.71E+10 J	1.81E+04[b]	1.40E+15	1678.03	
Earth cycle	1.45E+10 J	3.37E+04[b]	4.89E+14	588.39	
River water	5.58E+07 J	5.01E+04[b]	2.80E+12	3.36	
Subtotal			1.40E+15	1681.39	
Local nonrenewable resource input (*N*)					
Soil organic matter	1.82E+11 J	7.26E+04[b]	1.32E+16	15903.78	
Purchased nonrenewable input (F_N)					
Rent	9900 ¥	8.32E+11[c]	8.23E+15	9900.00	9900.00
Labor (90%)	3.28E+09 J	1.70E+06[d]	5.58E+15	6705.87	5695.31
Paper bag	7.79E+07 J	5.89E+04[e]	4.58E+12	5.51	8700.00
Package box	3.90E+07 J	5.89E+04[e]	2.30E+12	2.76	2500.00
Bulldozer	1562.55 ¥	8.32E+11[c]	1.30E+15	1562.55	1562.55
Mower	351.60 g	7.76E+09[b]	2.73E+12	3.28	93.75
Pump	9082.05 g	7.76E+09[b]	7.05E+13	84.74	703.20
Truck	15624.90 g	7.76E+09[b]	1.21E+14	145.80	781.20
Diesel oil	99.61 kg	2.82E+12[a]	2.81E+14	337.77	468.75
Gas	13.88 kg	2.82E+12[a]	4.13E+13	49.72	76.88
Compound fertilizer	2632.50 kg	2.99E+12[b]	7.87E+15	9464.67	8424.00
Nitrogenous fertilizer	270 kg	2.99E+12[b]	8.07E+14	970.87	540.00
Chemical pesticide	5878.40 ¥	8.32E+11[c]	7.31E+14	878.40	879.00
Seedlings	10800 ¥	8.32E+11[c]	8.98E+15	10800.00	10800.00
Subtotal			3.40E+16	40911.93	51124.64
Purchased renewable input (F_R)					
Labor (10%)	3.65E+08	1.70E+06[d]	6.20E+14	745.10	632.81
Manure	16875 kg	7.20E+1[f]	1.21E+16	14599.74	6750.00
Peanut bran	2700 kg	1.59E+11[g]	4.29E+14	516.21	7560.00
Subtotal			1.32E+16	15861.04	14942.81
Total input			6.18E+16	74358.15	66067.45
Yield					
Guava	45000 kg	*1.37E+12*[*]	6.18E+16	74358.15	130500.00
	7.72E+10 J[h]	*8.01E+05*[**]			

[a] Odum (1996).

[b] Campbell et al. (2005).

[c] http://sahel.ees.ufl.edu/database_resources.php?search_type=basic&country=CHN, the emergy/US$ in China in 2000, converted to 9.26E24 sej/yr baseline from 15.83E24 sej/yr baseline, and the exchange ratio between RMB and US$ in 2000 is 8.3.

[d] Lan et al. (1998). Converted to 9.26 E24 sej/yr baseline from 9.44 E24 sej/yr.

[e] Tilley (1999). Lumber, converted to 9.26 E24 sej/yr baseline from 9.44 E24 sej/yr.

[f] Cavalett et al. (2006). Converted to 9.26 E24sej/yr baseline from 15.83 E24 sej/yr.

[g] Shen (2001). Converted to 9.26 E24 sej/yr baseline from 9.44 E24 sej/yr.

[h] http://www.fumuqin.com/View.aspx?id=5047.

[*] Transformity calculated from this study.

[**] Specific emergy calculated from this study.

premium of 369% and 226%, respectively, as a result of the sale of their products. As the buyer of inputs to production, the banana and wampee systems got a little (7% and 1%, respectively) emergy benefit from the market exchange. This advantage in trade is revealed by the Emergy Exchange Ratio for their purchased inputs (EER_I), which was slightly higher than 1. In contrast, the papaya and guava systems lost 19% and 14%, respectively, of the average emergy value of their money in purchasing necessary inputs.

4.1.8. Emergy Benefit Ratio (EBR) and Emergy Benefit Ratio after Exchange (EBE)

The EBR takes into account any increases in natural capital that may occur as a result of production. After taking the increase in soil organic matter into consideration, the productivity of the banana system was the highest among the four fruit production systems examined, instead of the lowest as indicated by the EYR. The EBR of banana was 1.80, 1.59 and 1.60 times that of the papaya, guava and wampee growth systems, respectively. The EBE shows the effect of market exchange on the emergy balance of the ecological–economic system. A decline in this ratio compared to the value of the EBR indicates that natural capital within the system is not being adequately valued by the market. For the banana system, the EBE was lower than the EER_Y because no money (ΔQ_M) was received for the increase in natural capital realized in the overall exchange of ecological economic value. Also, the EER_Y for the other three fruit systems was equal to their EBE because no internal natural capital, soil organic matter here, was accumulated.

4.1.9. Emergy Index for Sustainable Development

The EISD showed that after taking the market effect on output into account, the order of the sustainability of the four fruit systems changed with the wampee system becoming slightly more sustainable than the guava system, followed by papaya and banana. Furthermore, after extending the consideration of market effects to both output and input, the sustainability of both guava and papaya decreased, while that of the other two systems slightly increased. When both the improvement in soil organic matter and the market

Table 5
Emergy and economic analysis table of the wampee production system (ha/yr).

Item	Raw data	Transformity (sej/unit)	Solar emergy (sej)	Em-value (EM¥)	Market value (¥)
Local renewable resource input (R)					
Solar radiation	4.70E+13 J	1.00E+00[a]	4.70E+13	56.45	
Wind	7.89E+08 J	1.47E+03[b]	1.16E+12	1.39	
Rain (geopotential)	1.48E+09 J	1.03E+04[b]	1.52E+13	18.34	
Rain (chemical)	7.71E+10 J	1.81E+04[b]	1.40E+15	1678.03	
Earth cycle	1.45E+10 J	3.37E+04[b]	4.89E+14	588.39	
River water	7.88E+07 J	5.01E+04[b]	3.95E+12	4.75	
Subtotal			1.40E+15	1682.77	
Local nonrenewable resource input (N)					
Soil organic matter	1.23E+10 J	7.26E+04[b]	8.93E+15	10738.00	
Purchased nonrenewable input (F_N)					
Rent	9900 ¥	8.32E+11[c]	8.23E+15	9900.00	9900.00
Labor (90%)	3.28E+09 J	1.70E+06[d]	5.58E+15	6705.87	5695.31
Package box	2.29E+07 J	5.89E+04[e]	1.35E+12	1.62	1466.67
Bulldozer	1562.55 ¥	8.32E+11[c]	1.30E+15	1562.55	1562.55
Mower	351.60 g	7.76E+09[b]	2.73E+12	3.28	93.75
Pump	9082.05 g	7.76E+09[b]	7.05E+13	84.74	703.20
Truck	15624.90 g	7.76E+09[b]	1.21E+14	145.80	781.25
Diesel oil	99.61 kg	2.82E+12[a]	2.81E+14	337.77	468.75
Gas	13.88 kg	2.82E+12[a]	4.13E+13	49.72	76.88
Compound fertilizer	1113.75 kg	2.99E+12[b]	3.33E+15	4004.28	3564.00
Nitrogenous fertilizer	675 kg	2.99E+12[b]	2.02E+15	2427.17	1350.00
Phosphorus fertilizer	675 kg	3.02E+12	2.02E+15	2453.07	351.00
Chemical pesticide	90 ¥	8.32E+11[c]	7.48E+13	90.00	90.00
Seedlings	8100 ¥	8.32E+11[c]	6.74E+15	8100.00	8100.00
Subtotal			2.98E+16	35865.87	34203.35
Purchased renewable input (F_R)					
Labor (10%)	3.65E+08	1.70E+06[d]	6.20E+14	745.10	632.81
Manure	5062.50 kg	7.20E+1[f]	3.64E+15	4379.92	2025.00
Peanut bran	1350 kg	1.59E+11[g]	2.15E+14	258.11	3780.00
Subtotal			4.48E+15	5383.12	6437.81
Total input			4.46E+16	53669.76	40641.17
Yield					
Wampee	16500 kg	*2.71E+12**	4.46E+16	53669.76	198000.00
	2.14E+10 J[h]	*2.08E+06***			

[a] Odum (1996).

[b] Campbell et al. (2005).

[c] http://sahel.ees.ufl.edu/database_resources.php?search_type=basic&country=CHN, the emergy/US$ in China in 2000, converted to 9.26E24 sej/yr baseline from 15.83E24 sej/yr baseline, and the exchange ratio between RMB and US$ in 2000 is 8.3.

[d] Lan et al. (1998). Converted to 9.26 E24 sej/yr baseline from 9.44 E24 sej/yr.

[e] Tilley (1999). Lumber, converted to 9.26 E24 sej/yr baseline from 9.44 E24 sej/yr.

[f] Cavalett et al. (2006). Converted to 9.26 E24sej/yr baseline from 15.83 E24 sej/yr.

[g] Shen (2001). Converted to 9.26 E24 sej/yr baseline from 9.44 E24 sej/yr.

[h] http://www.fumuqin.com/View.aspx?id=5047.

* Transformity calculated from this study.

** Specific emergy calculated from this study.

effect on output were taken into account, using $\mathrm{EISD}_{\Delta QY}$, the index values for all four fruit systems were identical to their EISD values. This result was found because no monetary reward was received for the accumulation of internal ecological capital.

4.1.10. Transformity and specific emergy

The transformities and specific emergies of the four fruits given in order, from high to low, are as follows: wampee > papaya > guava > banana. The transformity of wampee was 9.45, 2.60 and 1.14 times and, the specific emergy was 3.23, 1.89 and 1.31 times that of banana, guava and papaya, respectively.

The soil organic matter increased in the banana system, but the efficiency of the soil building process was only 0.13 times that of a temperate forest ecosystem (7.26E+04 sej/J, converted from Odum, 1996), and 0.02 times that of the *Acacia mangium* forest restoration system in subtropical China (3.75E+03 sej/J) (Lu et al., 2006).

4.2. Economic analysis

Among the four fruit production systems, guava had the highest cost per hectare for nonrenewable resources, and wampee the lowest, while for renewable resources, papaya had the highest cost per hectare and the banana system the lowest (Table 8). The papaya had the highest total cost per hectare cultivated, followed by the guava, wampee and banana (Table 8).

All of the fruit production systems spent more than 60% of the total cost on the purchase of nonrenewable resources (Fig. 4a). The different choices made between chemical and organic fertilizer caused the difference in cost structure to be largest between the banana and papaya systems (Fig. 4a and b). The banana system spent the highest percentage of the total production cost on nonrenewable resources, whereas nonrenewable resources were the lowest percent of the total cost for papaya (Fig. 4a).

The relatively high market price for wampee, 12 ¥/kg (Table 5), gave it the highest economic output/input ratio and benefit density

Table 6
Emergy analysis table of summary variables and indices for the four fruit production systems.

Item	Banana	Papaya	Guava	Wampee
Emergy flows (sej/ha/yr)				
Local renewable resources input (R)	1.40E+15	1.41E+15	1.40E+15	1.40E+15
Local nonrenewable resources input (N)	0	6.51E+15	1.32E+16	8.93E+15
Purchased nonrenewable input (F_N)	3.33E+16	4.01E+16	3.40E+16	2.98E+16
Purchased renewable input (F_R)	1.93E+15	1.01E+16	1.32E+16	4.48E+15
Total input (U, empower density)	3.67E+16	5.81E+16	6.18E+16	4.46E+16
Buying power of the money spent to purchase inputs ($F_{RM} + F_{NM}$)[a]	3.29E+16	6.18E+16	5.49E+16	3.38E+16
Yield (Y)	3.67E+16	5.81E+16	6.18E+16	4.46E+16
Buying power of the money received for the yield (Y_M)[a]	8.30E+16	1.12E+17	1.09E+17	1.65E+17
Increase in natural capital storage (ΔQ)	3.67E+16	0	0	0
Emergy indices				
Emergy Self-sufficiency Ratio (ESR = $(R+N)/U$)	0.04	0.14	0.24	0.23
Environmental Loading Ratio (ELR = $(N+F_N)/(R+F_R)$)	10.01	4.06	3.24	6.60
Emergy Yield Ratio (EYR = $Y/(F_R+F_N)$)	1.04	1.16	1.31	1.30
Emergy Sustainability Index (ESI = EYR/ELR)	0.10	0.29	0.40	0.20
Emergy Benefit Ratio (EBR = $(Y+\Delta Q)/(F_R+F_N)$)	2.08	1.16	1.31	1.30
$\mathrm{EER_I} = (F_R+F_N)/(F_{RM}+F_{NM})$	1.07	0.81	0.86	1.01
$\mathrm{EER_Y} = Y_M/Y$	2.26	1.93	1.76	3.69
$\mathrm{EBE} = (Y_M+\Delta Q_M)/(Y+\Delta Q)$	1.13	1.93	1.76	3.69
$\mathrm{EISD} = \mathrm{EYR} \times \mathrm{EER_Y}/\mathrm{ELR}$	0.24	0.55	0.71	0.73
$\mathrm{EISD_{YI}} = \mathrm{EYR} \times \mathrm{EER_Y} \times \mathrm{EER_I}/\mathrm{ELR}$	0.25	0.45	0.61	0.74
$\mathrm{ESI_{\Delta Q}} = \mathrm{EBR}/\mathrm{ELR}$	0.21	0.29	0.40	0.20
$\mathrm{EISD_{\Delta QY}} = \mathrm{EBR} \times \mathrm{EBE}/\mathrm{ELR}$	0.24	0.55	0.71	0.73
$\mathrm{EISD_{\Delta QYI}} = \mathrm{EBR} \times \mathrm{EBE} \times \mathrm{EER_I}/\mathrm{ELR}$	0.36	0.45	0.61	0.74
$\mathrm{EYR} \times \mathrm{EER_Y} \times \mathrm{EER_I}$	2.52	1.82	1.98	4.87

[a] If spent in the general economy. $Y_M = M_Y$ (¥) × emergy to money ratio (sej/¥); $F_{RM} = M_{FR}$ (¥) × emergy to money ratio (sej/¥); $F_{NM} = M_{FN}$ (¥) × emergy to money ratio (sej/¥) (Fig. 2).

among the four systems studied (Table 8). Although the papaya system had a relatively high output value, it also had the highest cost structure, which gave it the lowest output/input ratio and the second lowest benefit density (Table 8). Although both the guava and papaya had a higher benefit density than the banana system, the relatively high cost per hectare made their economic output/input ratio lower than the banana system (Table 8).

Table 7
Transformities and specific emergies of the products of the four fruit production systems.

Product	Transformity/specific emergy	
	sej/J[a]	sej/g
Banana	2.20E+05	8.38E+08
Soil organic increase under banana	2.09E+05	
Papaya	1.83E+06	2.07E+09
Guava	8.01E+05	1.37E+09
Wampee	2.08E+06	2.71E+09

[a] Energy contents were taken from http://www.fumuqin.com/View.aspx?id=5047, June 24, 2008.

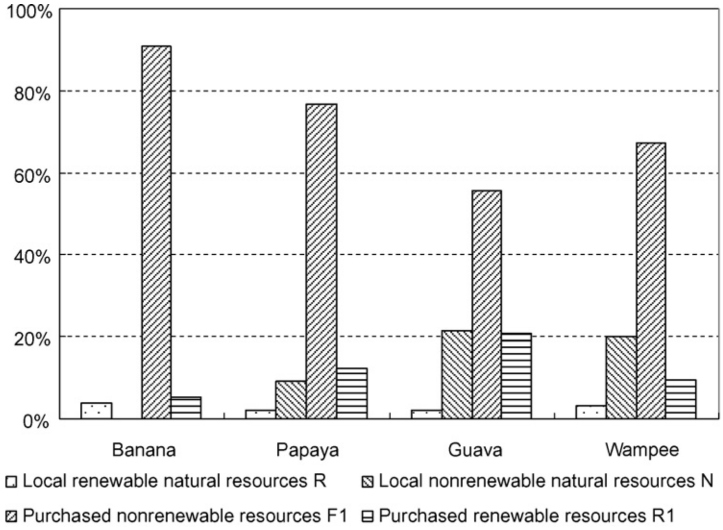
5. Discussion

5.1. Management of farmland for fruit production on reclaimed wetland

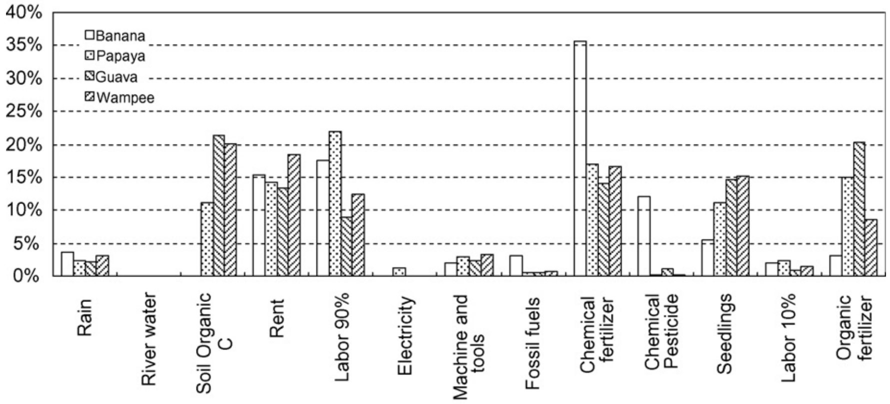
Compared with the three small family farms in Brazil studied by Agostinho et al. (2008), the four fruit production systems were highly dependent on economic resources. The transformity and specific emergy of the bananas produced in this system (2.20E+05 sej/J and 8.38E+08 sej/g) was greater than that of the bananas produced from all six production systems in the French West Indies (1.49E+05 sej/J to 1.82E+5 sej/J, and 6.73E+08 sej/g to 8.19E+08 sej/g) evaluated by De Barros et al. (2009, converted to 9.26E+24 sej/yr planetary baseline from 15.83E+24 sej/yr), which showed that the banana production system evaluated was less efficient than the least efficient banana production systems in Guadeloupe. The transformity of the papaya (1.83E+06 sej/J) produced from the systems that we evaluated was larger than that of papaya (1.37E+06 sej/J) produced in the polycultural rotation system of the Lacandon Maya in Chiapas, Mexico, studied by Martin et al. (2006), which indicates that there are still something the modern papaya cultivation could learn from the traditional polyculture. The specific emergies of all three newly introduced fruits

Table 8
Economic structure and benefit analysis of the four fruit production systems.

Item	Banana	Papaya	Guava	Wampee
Economic flows (¥/ha/yr)				
Local renewable resources input (M_R)	0	0	0	0
Local nonrenewable resources input (M_N)	0	0	0	0
Purchased nonrenewable input (M_{FN})	36636.78	47115.95	51124.64	34203.35
Purchased renewable input (M_{FR})	2953.75	27242.81	14942.81	6437.81
Total input ($M_I = (M_{FN} + M_{FR})$)	39590.53	74358.76	66067.45	40641.17
Market value of output (M_Y)	99825.00	135000.00	130500.00	198000.00
Economic evaluation indices				
Economic output/input ratio = M_Y/M_I	2.52	1.82	1.98	4.87
Benefits density = $(M_Y - M_I)$/area (¥/ha/yr)	60234.47	60641.24	64432.55	157358.83



(a) **Structures of classified emergy inputs to the 4 fruit production systems**



(b) **Structure of detailed emergy inputs to the 4 fruit production systems**

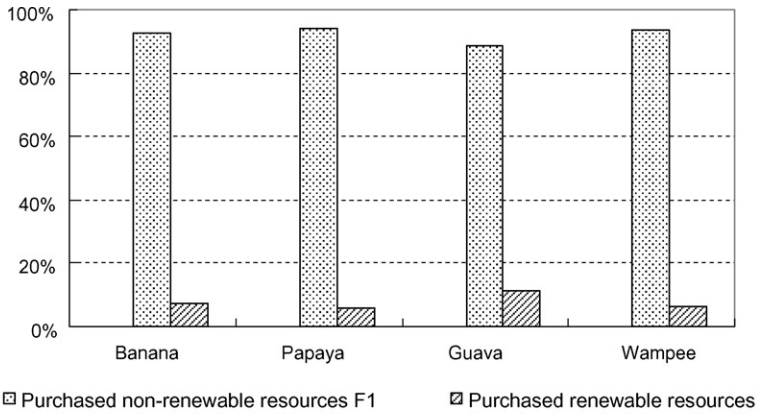
Fig. 3. Structure of the emergy inputs to the four fruit production systems.

were greater than that of oranges from Florida, US (1.12E+09 sej/g), studied by Brandt-Williams (2002), and that of grapes from Italy (9.72E+08 sej/g) studied by Bastianoni et al. (2001), which showed a relatively low efficiency of the three newly introduced fruit production systems. However, the specific emergy for traditional bananas grown in Wanqingsha was less than that of oranges from Florida and grapes from Italy, indicating that the traditional fruit culture system in this area is comparable in efficiency to that of culture systems for a primary fruit product of Florida (oranges) and Italy (grapes).

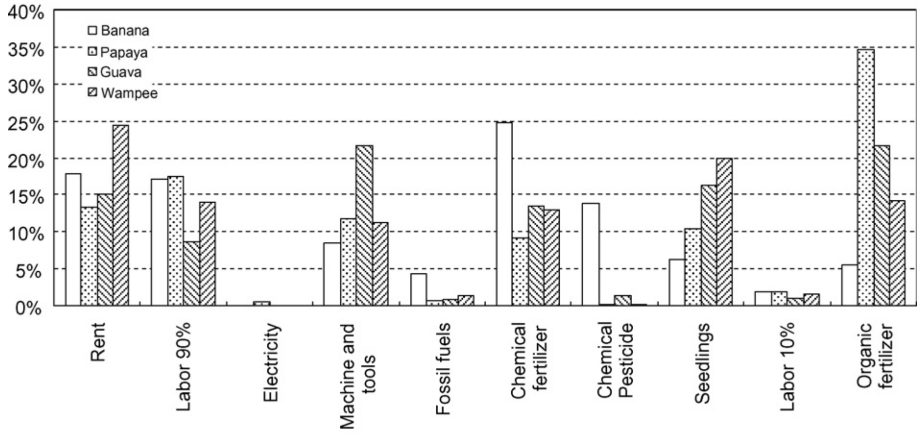
The three newly introduced fruit culture systems have Emergy Yield Ratios slightly greater than one and relatively low Environmental Loading Ratios (from 3.24 to 10.01). Although these EYRs may seem low, they are typical of agricultural systems (Lu et al., 2002; Martin et al., 2006; De Barros et al., 2009). In addition, the new fruit systems have EBEs higher than that of traditional banana culture; however, this relative advantage is largely due to the fact that the benefit of increasing soil organic matter is not uncompensated. In contrast, the EBR shows that banana is still competitive with the new fruit systems on an emergy basis when both market products and natural capital increases are considered.

The new fruits economic output/input ratios are comparable to traditional banana culture, and their economic benefit densities are higher than that of bananas. Thus, from both an emergy and an economic standpoint, the majority of evidence indicates that these newly introduced fruit culture systems are good choices to replace some of the large area, presently in bananas, which is now seriously threatened by Panama disease.

Once the effects of market exchange on sustainability were considered using the EISD, wampee became the most sustainable production system exceeding the sustainability of the guava system by a small amount. This observation points out that emergy indices, like the EISD that factor market conditions into the index value, are sensitive to changes in prices. Price changes and volatility can drastically alter the choices that might be made based on such indices. For this reason, we recommend that the indices based on emergy alone (e.g., ESI, EBR, $ESI_{\Delta Q}$) be the first piece of information taken into account for decision-making. Secondarily, factoring in the effects of market conditions can yield valuable information about the effective emergy balance between trading partners, which may also be of interest to decision-makers. However, an underlying assumption in the calculation of such indices as the EISD is that market conditions are in a steady state or dynamic equilibrium. If equilibrium conditions are perturbed or if there is excessive volatility in prices, this must be taken into account in evaluating emergy indices that have been adjusted for the effects of market exchanges before they are used in decision-making.



(a) **Structure of classified economic costs of the 4 fruit production systems**



(b) **Structure of the detailed economic costs of the 4 fruit production systems**

Fig. 4. Structure of the economic costs to the four fruit production systems.

Measurements of soil organic matter in the plots clearly showed a dramatic reduction of the internal natural capital, in all three newly introduced fruit systems, whereas this resource accumulated in the traditional banana system due to the application of the "straw returning" technology. The fact that the EBR, which takes soil organic matter into account, was over 1.6 times greater in banana than in the three new fruit production systems, clearly showed a large potential for further optimization of the newly introduced systems, with regard to the preservation of natural capital. The annual increment of soil organic matter was considered to be a co-product of fruit output, based on the assumption that banana litter fall and prunings were the primary source of increases in SOC. The change of SOC was based on three soil cores per production system taken at the beginning and end of the sampling year. This sample regime is not frequent enough to express the fluctuation of the soil nutrients in these three agriculture systems over the course of a year; however it may be sufficient to obtain a first-order estimate of the net change in organic matter in each experimental plot that we sampled. Furthermore, without measurement of the rates of litter fall and the microbial decomposition rate of organic matter we cannot make a budget for SOC and determine the turnover time of the SOC pool; therefore, the transformity of the soil organic matter under the bananas could not be determined exactly for these sites. These factors may cause some error to be introduced into the calculation of EBR and EBE as well as the EISD and ESI after considering the change of storage ($\mathrm{EISD}_{\Delta Q}$ and $\mathrm{ESI}_{\Delta Q}$, respectively).

The reason for the rent difference between the banana production system and the other three systems is solely due to the difference in the start time of the lease. No adjustment for differences in soil fertility or other factors was made in determining rent. The Em-value of soil improvement in the banana production system was 45705.82 Em¥/ha/yr or 46% of the total economic output of the system. Even if the transformity for soils from Odum (1996) is used, which is 0.35 times that of the soil made by the banana production system, the Em-value of soil improvement will be high (5941.76 Em¥/ha/yr). When the Em¥ value (5941.76 Em¥/ha/yr) of soil building was included, the economic benefit density of the banana production system was higher than that of the papaya and guava production systems instead of lower. Similarly, if the decrease in Em-value of the soil organic matter is considered, the land rent paid by the papaya, guava and wampee production systems will be 7822.95 Em¥/ha/yr, 15903.78 Em¥/ha/yr and 10738.00 Em¥/ha/yr, respectively, more than is currently being paid. Although at present it might be hard to apply this insight in practice, these results point the way toward the future optimization of the land rental system that is needed to ensure sustainable production.

5.2. Emergy accounting

Detailed network analysis is an essential complement to index evaluation in emergy analyses, especially those done for purposes of optimization. By showing the structural reasons behind differences in the emergy indices, optimization points and strategies may be discovered. For example, in this study the guava production system had the lowest ELR, but the detailed analysis of its input structure also showed that despite this fact it had the highest use of local nonrenewable resources, thus pointing toward a way to further optimize the guava production system. The increase of soil organic matter in the banana system, on the other hand, is clearly neglected by the ELR as a mitigating factor for its high environmental load. Structural analysis of this system showed that further optimization may depend on decreasing the input of purchased chemical fertilizers, which account for 47% of the nonrenewable empower used.

The analysis of changes in storage is an essential part of the evaluation of systems that are not in steady state. Steady state is often assumed but seldom exists in reality, whereas pulsing and cycling are more common general phenomena (Odum et al., 1995). One of the useful features of emergy accounting is that it takes the environmental contributions to economic production into consideration in the evaluation, especially with regard to nonrenewable natural resources, since their quantities are finite and will not be extracted at the current rate in the future. When the cost of natural resources is being calculated, the accumulation of internal natural capital, as well as output, should be accounted for to gain a holistic picture of the system. When increases in storage and the output from the system are all or in part co-products, the emergy benefit is equal to their sum, since they have not interacted, and the removal of an output does not affect a storage increase, which is kept in the system.

The meaning of the ELR and ESI here is a little different from that in Ulgiati and Brown (1998), since the purchased inputs were classified into renewable and nonrenewable moieties in this study, instead of taking all of them as nonrenewable input. That means highly developed systems do not have to be highly nonrenewable, if they can improve the percentage of renewable sources in their purchased input. This clearly shows a possible development direction for the world. Although this classification is a step toward classifying systems more exactly, it also means more work and it will be difficult to obtain accurate values for all of the inputs due to limited data availability or other constraints. For example, in this study, manure and peanut bran were taken as purchased renewable input which is clearly not entirely accurate since their production processes use some nonrenewable resources, such as labor and electricity.

5.3. Complementarities between emergy accounting and economic analysis

Emergy accounting and economic analysis are based on different valuation theories, and consequently focused on different valuation questions, and it is not surprising that they can produce different results, even for analyses of the same system.

Emergy accounting includes all the contributions from which value in an economic production process is derived. The market economy only recognizes the contributions of human service to value and gives no value to the work of the environment. Therefore, as a general rule, the Em-money value of a good or service is expected to be greater than the monetary value of the same product as determined by equilibrium market mechanisms (Campbell and Cai, 2007). In this study, 3.82%, 13.63%, 23.65% and 23.14% of the emergy input to fruit production was missed in the economic analysis (Fig. 3a). These deficits are similar to those observed by Agostinho et al. (2008) and Lefroy and Rydberg (2003) for agricultural products. On the other hand, market effects cause prices to pulse, which can make the monetary value of some goods and services temporally exceed their emergy value (Campbell and Cai, 2007), which is similar to what happened in this study with regard to the price for fruit, especially for wampee, which was scarce on the local market during the study period.

For the above reason, the total input per hectare, the purchased nonrenewable input and the purchased renewable input for the four fruit production systems displayed different orders when ranked by their magnitudes measured in emergy or monetary units (Tables 6 and 8). Using emergy, the papaya production system had the highest F_N/ha/yr and the guava production system had the highest F_R/ha/yr and U/ha/yr, while in monetary terms, the guava production system had the highest F_N/ha/yr, and the papaya production system had the highest F_R/ha/yr and U/ha/yr. When considering the productivity of purchased inputs, the evaluation results of the two methods were different too, with the Emergy Yield Ratio ranking guava > wampee > papaya > banana but the ranking obtained from the economic output/input ratio was wampee > banana > guava > papaya.

Emergy accounting considers the environmental as well as the economic basis for wealth, while economic analysis is focused on the value of products and processes from the human perspective. Owners and stakeholders seeking their own short-term interests may find it hard to accept emergy accounting results, when market effects remain unconsidered. Similarly, without taking environmental contributions to wealth into consideration, economic analysis does not capture the rapid loss of internal natural capital from the system, which leads to system failure in the long run.

The use of emergy, together with economic evaluation methods, can provide additional information to guide human activities, such as the design and optimization of production processes of all kinds and determining the feasibility of ecological versus standard engineering designs for solving environmental problems.

5.4. Integration of emergy accounting and economic analysis

Although emergy evaluation is a more holistic method for evaluating ecological–economic systems compared to economic analysis, the majority of decision-makers rely on economic analyses to judge between alternative policies. Clearly, economic analysis does not provide complete information for making informed decisions with regard to setting public policies on the environment. For these reasons, further efforts toward establishing a working relationship between these two fields is desirable as suggested by Maud (2007). In particular, we believe that the integration of these two valuation methods is essential to fill the need of satisfying multiple requirements for sustainable development. In this regard, the generally accepted goal of sustainability is to meet the needs of the present generation without sacrificing the capability for future generations to meet their own needs (WCED, 1987).

There is a general opinion among economists that market factors such as the relationship between supply and demand etc. keep market prices pulsing around the long-term value of goods and services that is determined by their optimum production processes (Samuelson and Nordhaus, 2001). Although the long-term mean price is equal to the value of a good or service, and benefit and loss comes from the difference between long-term value and current price, this can also be seen as the temporal “unfairness” of market exchange, which can dramatically affect business decisions and the economy. The quantity of money and its rate of flow in a specific area during a specific period can be measured, which might be taken as the monetary value for all of the goods and services in that specific area during that specific period. The emergy/money ratio is an index proposed as a conversion coefficient between emergy and the average monetary value of human service in the system (Odum, 1996). On a national basis, it is defined as the total annual emergy use by a nation in solar emjoules divided by the gross economic product expressed in monetary units.

The EER is another useful index that can link emergy and economic analyses, which could fill some evaluation needs for specific systems. There is a gap to fill because the emergy/money ratio is only a mean ratio for all of the goods and services on a system-wide scale, which usually is not equal to the EER for specific goods or services.

The real assets left in an economic system after exchange are represented by the buying power of the money received from the market for the sale of its products (Odum, 1996). With this in mind, Lu et al. (2003) extended the Emergy Sustainability Index (ESI = EYR/ELR) to construct the Emergy Index for Sustainable Development (EISD = EYR × EER/ELR). One problem for the EISD is that the EER is just a measure of the current market exchange for the output from the system which is equal to $Y_M/Y = (M_Y \times \text{the emergy to money ratio})/Y$; however, market exchanges also determine the inputs for most open ecological–economic systems. The Emergy Exchange Ratio for purchased input ($\mathrm{EER_I} = (F_R + F_N)/(F_{RM} + F_{NM})$) relates the emergy contained in purchased inputs to the economic value of the human service in an average commodity purchased from the larger system. Its calculation is the emergy flowing into the system (the numerator) divided by the emergy that can be purchased on the general market by the money flowing out of the system (the denominator).

The EYR is an indicator of the productivity of the purchased inputs, $F_R + F_N$. Taking the market change into account, the actual cost to the system for the purchased input is the buying power ($F_{RM} + F_{NM}$) of the money flowing out from the system that is used to purchase the inputs, while the emergy left in the system represents the buying power of the money received from the market for its products (Y_M) plus or minus any gain or loss of emergy that occurs in the purchase of inputs. Thus, considering the effects of market exchange on both input and output, the result of economic investments for the system is $\mathrm{EYR} \times \mathrm{EER_I} \times \mathrm{EER_Y}$.

Since

$$\mathrm{EYR} = \frac{Y}{(F_R + F_N)}$$

$$\mathrm{EER_I} = \frac{F_R + F_N}{F_{RM} + F_{NM}} = \frac{F_R + F_N}{(M_{FR} + M_{FN}) \times \text{emergy to money ratio}}$$

$$\mathrm{EER_Y} = \frac{Y_M}{Y} = \frac{M_Y \times \text{emergy to money ratio}}{Y}$$

Thus

$$\begin{aligned}
\mathrm{EYR} \times \mathrm{EER_I} \times \mathrm{EER_Y} &= \frac{Y}{F_R + F_N}\,\frac{F_R + F_N}{F_{RM} + F_{NM}} \times \frac{Y_M}{Y} \\
&= \frac{Y}{F_R + F_N} \times \frac{F_R + F_N}{F_{MR} + F_{MN}} \times (\text{emergy to money ratio}) \times \left(M_Y \times \frac{\text{emergy to money ratio}}{Y}\right) \\
&= \frac{M_Y}{M_{FR} + M_{FN}} \\
&= \frac{\text{economic output}}{\text{economic input}}.
\end{aligned}$$

The above argument demonstrates and the results of this study confirmed (Tables 6–8) that the economic output/input ratio is related to emergy as the product of three factors: the market exchange, i.e., emergy purchasing power, of both the input $[(F_R + F_N)/(F_{RM} + F_{NM})]$ and output (Y_M/Y), and the ability of the system or process to exploit local resources $[Y/(F_R + F_N)]$. As a result of this analysis, we propose that the EER be used as a bridge between emergy and economic value, when applied to both the inputs to and outputs from a system. These indices show the relative advantages and disadvantages in the exchange of real wealth (emergy) bought and sold by a specific system or process, and may be similar to the function of the emergy to money ratio used on the national and regional scales. One caveat is that the price structure of the inputs and outputs must be in a steady state for the time examined for such equivalences to be valid. A similar constraint applies to the emergy to money ratio, which must be determined for the year of the study.

6. Conclusions

Ecological engineering is the design of sustainable systems, consistent with ecological principles, which integrates human society with its natural environment for the benefit of both (Mitsch and Jorgensen, 2003, 2004). The fruit production systems examined in this study may be considered to be ecological engineering systems, because they take advantage of the ecosystem principles as they combine natural resources, e.g., solar radiation, rain, soil nutrients, and outputs from the economy, e.g. seedlings, services, fertilizers, etc., to generate useful products, i.e., fruit for people. The main goal of the ecological engineering studies and practices is to maximum the mutual benefit to both humanity and nature. Emergy evaluations have been widely used in ecological engineering, including agro-ecological engineering, to compare the contributions of the environment to those proposed from the economy so as to maximize both, and this methodology has been valuable in evaluating stored assets and in providing incentives for environmental management, based on emergy and Em-value (Odum and Odum, 2003). In this study, the results of our analyses point the way toward ecological engineering designs of fruit production systems that will increase emergy benefits to ecosystems and to society. Some specific innovations and strategies for accomplishing this end and a brief summary of our results are given below.

(1) Newly introduced fruit production systems in reclaimed wetland areas around the Pearl River Estuary have expanded quickly as a result of the relatively high market price for their products, but at the cost of a decrease in local nonrenewable resources, specifically, soil organic matter. Soil organic matter is being depleted, even though large quantities of organic fertilizer have been used to take the place of chemical fertilizer. Some traditional technologies might be useful for optimization of the three newly introduced fruit production systems, e.g., rotation and keeping the litter and tree prunings in the field to build soil organic matter. In addition, the environmental impacts from the loss of soil organic matter might be compensated by a policy decision to adjust the cost of land rental, to promote long-term welfare and regional sustainability.

(2) Since many system storages are not in steady state, an emergy evaluation of changes in natural capital within the system must be taken into consideration for a complete and accurate characterization of the entire ecological–economic system.
(3) Emergy accounting and economic analysis are complementary valuation methods. Emergy analysis is a biophysical donor-based valuation method that takes environmental contributions to economic production into consideration; these inputs are missed in most economic analyses. Economic analysis is a receiver-based value system, which accounts for value from the perspective of consumer preferences that are not usually considered in emergy syntheses. It may be possible to integrate the two methodologies into a combined valuation system, which measures value from both a donor and a receiver perspective and relates the two. The extension of the EER to the inputs and outputs of a system and combining it with the EYR can provide a bridge for the integration of the two methods by showing more exactly how the two value calculations are related. This method of evaluation when applied to specific systems and processes may serve a similar function to the emergy to money ratio applied to systems on macroscopic national and regional scales.

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