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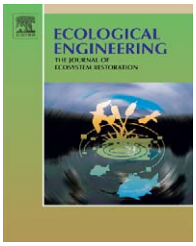

Emergy synthesis of an agro-forest restoration system in lower subtropical China

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ABSTRACT

The low subtropical zone is the most populated and seriously degraded area in China; therefore, highly efficient restoration of degraded lands is the key to sustainable development of this region. An agro-forest restoration mode consisting of an *Acacia mangium* forest, a *Citrus reticulata* orchard, a *Pennisetum purpureum* grassland, and a fishpond has been applied widely in this region. Emergy synthesis was performed at the system and subsystem levels of organization to clarify the structural and functional attributes of this restoration system for further optimization. Emergy indices, including four new indices, the emergy restoration ratio (ERR), the ecological economic product (EEP), the emergy benefit ratio (EBR), and the emergy benefit after exchange (EBE), were formulated to evaluate the ecological and economic benefits of this restoration mode. Benefits were determined for the separate subsystems and for the system as a whole, based on the classification of human services into management and harvest costs. The emergy sustainability index (ESI) of the agro-forest restoration system was 16 and the emergy index for sustainable development (EISD) was 122, demonstrating that this system produces high ecological and economic benefits and that it is a good alternative for the restoration of hillside areas in subtropical China.

1. Introduction

The low subtropical region of China refers to the nearby areas on both sides of the Northern Tropic of Cancer. It ranges over Fujian, Guangdong, and Guangxi to Yunnan Province with an area of 250,000 km^2, and it is one of the most populated regions in China. In recent decades, over-intensive human activities (e.g., industrialization and urbanization) together with unreasonable development and ignorance of the need for environmental protection and renovation have largely destroyed many formerly natural ecosystems in China. It was estimated in 1990 that China had degraded lands totaling about 1.5 million km^2. The low subtropical zone is a region with more serious degradation than found in most of China. More than 50% of the soil in the low subtropical area is laterite, formed from the earth's weathered crust of granite. Serious soil erosion occurring after forest destruction is the major factor that exacerbates the degradation of ecosystems. These ecosystems are characterized by impoverished soil, exhausted water sources and deteriorating ecological environments that restrict the development of agricultural production and have grave impacts on the living space and the quality of life experienced by humans. Obviously, restoration of vegetation is the key to enhancing regional productivity, improving the ecological environment, ensuring sustainable use of resources and sustainable development of the economy.

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The *Acacia mangium* forest–orchard–grassland–fish pond system, developed by the South China Institute of Botany of the Chinese Academy of Sciences (CAS), was applied in the Heshan Hillside Open Station in lower subtropical China, which was covered by grass after monsoon evergreen broadleaf forest was cut (Yu and Peng, 1996). With fast forest growth and efficient agricultural production, the *A. mangium* forest–orchard–grassland–fish pond agro-forest restoration mode has important benefits for both ecological restoration and the social economy. Approved by local government and farmers, this mode has been applied at a regional scale in the Pearl River Delta of lower subtropical China. From 1989 to 1996 in Heshan City alone, the economic benefit derived from these agro-forest modes has risen from 30% to 84%. The total benefits from these modes had reached 3.346 billion yuan by 1996 and the economic output/input ratio was higher than 5 (Yu and Peng, 1996; Peng et al., 2003).

Many ecological studies have been done on this system, such as evaluations of the material cycle (Ding et al., 1995), soil structure (Li et al., 1995a, b), dynamics of biodiversity, biomass, energy, microclimate and hydrology (Zhang et al., 1995; Fu et al., 1995; Fang et al., 1995; Lin et al., 2000, 2003; Zeng et al., 2000; Yan et al., 2002; Ren et al., 2000). Some pure economic statistical calculations have also been done (Peng et al., 2003). All of these studies were based on their own unique quantifiable units of measure. Lacking a general unit and method to integrate different ecological and economic properties, many problems, such as how to integrate all of the parts together to obtain a holistic evaluation of ecological and economic effects on the system and how to determine the weaknesses of this mode from the standpoint of providing a "total combined benefit to nature and humanity", were still unsolved.

Emergy is defined as the sum of all inputs of available energy directly or indirectly required by a process to provide a given product or service, when the inputs are expressed in units of the same form (or type) of energy, usually solar emjoules (sej) (Odum, 1996; Brown and Ulgiati, 1997). Developed over the last three decades, Emergy Systems Theory (Odum, 1994, 1996) provided a valuable unit (the emjoule) and method (emergy synthesis) for overcoming the "metric" problems, by normalizing all products and services of the system to a unit of measure that represents the quantity and quality of work being created and maintained by that system (Odum, 1996; Tilley and Swank, 2003). In emergy synthesis, all kinds of material and energy flows are transferred to the same unit, solar emjoules, by multiplying the various available energy values of the flows by the appropriate solar transformity (sej/J), defined as the solar radiation (solar emjoules) required directly and indirectly to create another form of available energy (exergy) (Odum, 1988). Money flows can be transferred to solar emergy units, through the emergy-to-money quotient, defined as the total emergy used in a year by a state or nation divided by the gross economic product expressed in local monetary units (Odum, 1996). Based on the accelerating rate of scholarly publications centered on emergy synthesis, it appears that the methodology is maturing to a respected form of integrated ecological economic evaluation (Tilley and Swank, 2003; Brown et al., 2000, 2003). Emergy assessment has been successfully applied to some agricultural and forest ecosystems (Odum and Arding, 1991; Ulgiati et al., 1993; Lan et al., 1998; Liu et al., 1999; Zhang et al., 1999; Odum et al., 2000; Lu et al., 2002a; Tilley and Swank, 2003), but most of these studies only considered one level of system organization, i.e., without subsystem and mother system levels of analysis. To better understand how to document and account for the environmental effects of economic processes, more and more attention has been paid to the evaluation of co-products and their effects (Bastianoni and Marchettini, 2000; Ulgiati and Brown, 2002; Pykh et al., 2000). In restored forest systems, changing soil chemistry is a co-product of the restoration process and an important indicator of overall environmental effects (Yu and Peng, 1996; Ren and Peng, 2001); however it has seldom been taken into account in emergy evaluations. Furthermore, a full suite of emergy indices for evaluating the environmental effects and economic benefits of restoration, both separately and together, is not yet developed, although it would be really helpful to decision-makers.

In this study, emergy synthesis was done at the system and subsystem levels to make clear the structural and functional attributes of the restoration system for further optimization. The change in soil quality within each subsystem was measured and accounted for in the emergy required for subsystem products or as an increase in stored ecological capital within the system. The increases in the emergy of ecological capital, e.g., soil and biomass, within the restoration ecosystem were added to the emergy of the yield to give a synthetic measure of total benefit, the ecological economic product (EEP). In addition, three new emergy indices, the emergy restoration ratio (ERR), the emergy benefit ratio (EBR); and the emergy benefit after exchange (EBE); were proposed and calculated in addition to the emergy yield ratio (EYR), to shed some light on ecological and economic processes, separately. Two emergy indices, the emergy sustainability index (ESI) (Ulgiati et al., 1995; Brown and Ulgiati, 1997) and emergy index for sustainable development (EISD) (Lu et al., 2002a,b); were extended and calculated here to fill the need for holistic evaluation of sustainable development and to further optimize the system under study.

2. Location

The Heshan Hillside Restoration Open Station of CAS was established in 1986, as a result of searching for locations to develop and test sustainable restoration modes in this degraded area. Located in Center Heshan City, Guangdong Province, South China, at east longitude 112°53′15″–112°54′00″, and north latitude 22°40′07″–22°41′07″, Heshan Station belongs to the low hill area with an altitude less than 100 m. The soil is laterite formed from the earth's weathered crust of granite (Yu and Peng, 1996).

The *Acacia mangium* (big-leaf acacia) forest–*Citrus reticulata* (mandarin orange) orchard–*Pennisetum purpureum* (elephant grass) grassland–fish pond system is one of the restoration systems used in the catchment area of Heshan Station, which was originally covered with grassland degraded from evergreen broad-leaved forest by deforestation. In 1983, the leguminous plant *A. mangium* was planted on the sterile top of the hill in an effort to restore vegetative structure, decrease erosion and increase soil fertility. *Citrus reticulata* was planted on the hillside 2 years later to make full use of the fertile soil on

Fig. 1 – Photograph of the agro-forest restoration system in 2002 (digital picture).

the hillside and take advantage of the runoff and silt deposition from the hilltop forest. Then a fish pond was built at the foot of the hill, and in 1986 *Pennisetum purpureum* was planted in the area between the fish pond and the orchard to produce grass forage for the pond fish. Each year in December, all of the pond-mud was dug up and fed back to the orchard as fertilizer. Fruit and fish were sold on the market for economic benefits. Respectively, the areas of forest, orchard, grassland and fish pond are 1.3, 0.87, 0.29, and 0.3 ha, with the mean altitudes of 70, 47.5, 35 and 25 m. Fig. 1 is a photograph of this system taken in 2002.

3. Methods

3.1. *Biomass*

All of the *A. mangium* trees and orange trees were marked and their height (*H*), diameter at breast height (DBH) and canopy area (CA) were measured. Three trees with characteristics close to the average *H*, DBH and canopy area were harvested in these two subsystems, for the determination of biomass and energy of the trees. The aboveground biomass of the grass was measured after it was cut.

3.2. *Litter and soil*

Five 1 m^2 litter traps were installed in the *A. mangium* subsystem and in the orchard for the collection of litter. At the end of every month, the litter in these traps was collected and brought back to the laboratory where wet weight and dry weight were measured.

Five 1 m soil cores were collected from *A. mangium*, the orange orchard, and the grassland using 3.7 cm diameter coring tubes. Every soil sample was classified into seven levels (0–10, 10–20, 20–30, 30–40, 40–50, 50–75, 75–100 cm) according to depth, for the measurement of organic matter, total nitrogen, total and available phosphorus, density, pH, etc.

3.3. *Runoff and evapotranspiration*

The rainfall data came from five rain-gauges. Additionally, 15 rain-gauges were installed to measure the through-fall under the *A. mangium* forest. Seven tipping bucket rain gauges and seven tubes were installed to measure the stem flow and percolation. The surface runoff data were obtained from runoff measurements in the field. Evapotranspiration data were calculated through an evapotranspiration function established by Zhou (1997) for *A. mangium* forest, and an energy-budget variant of the eddy correlation approach for the grassland subsystem, based on the data collected from a micro-weather station about 100 m away from *A. mangium* subsystem, and from an LI188B Integration Quantum Radiometer Photometer CM-1, a net radiation instrument placed in the two subsystems (Yan et al., 2002; Shen et al., 2000).

3.4. *Management*

The background data on the system, such as the starting time of the four subsystems, the output of fruit and fish, and the service costs of management for the whole system and its four subsystems' were collected from the historic database of Heshan Station.

3.5. *Emergy evaluation*

Following the general methods of emergy synthesis given by Odum (1996, 2000), boundaries of the agro-forest restoration system and its four subsystems were defined first (Fig. 3). The temporal boundary was defined as 1 year, and average annual data from every subsystem were used for the evaluation. Based on the detailed calculation of the solar emergy inflows to each subsystem and to the system as a whole (Appendix A, and Table 1), the input and output emergy flows were summed by category and reported out, for both the subsystems and the whole system, simultaneously (Table 2).

Table 1 – Emergy accounting table

Notes	Item	Raw data	Units	Solar transformity (sej/unit)	Solar emergy (sej)
A. mangium forest					
1	Sun	5.70E+13	J	1.000E+00	5.704E+13
2	Evapotranspiration, chemical	6.576E+10	J	2.81E+04	1.848E+15
3	Runoff, geo-potential (from rain directly)	5.017E+07	J	2.72E+04	1.365E+12
	Renewable emergy absorbed directly (2 + 3)				1.849E+15
4	Labor for planting and seedling management	1.228E+07	J	1.700E+06[a]	2.088E+13
5	Net general annual increase of forest biomass	2.807E+11	J	*5.544E+03*	1.556E+15
6	Litter (staying in forest)	4.850E+10	J	*5.544E+03*	2.689E+14
7	Litter (to orange orchard)	8.118E+09	J	*5.544E+03*	4.500E+13
8	Runoff to orchard, geo-potential	3.010E+08	J	2.72E+04	8.188E+12
9	Soil improvement (organic increase)	4.982E+11	J	*3.753E+03*	1.870E+15
Orange orchard					
1	Sun	3.818E+13	J	1.00E+00	3.818E+13
2	Evapotranspiration, chemical	4.401E+10	J	2.81E+04	1.237E+15
3	Runoff, geo-potential (from rain directly)	7.991E+07	J	2.72E+04	2.173E+12
4	Runoff, geo-potential (from forest absorbed in orchard)	7.527E+07	J	2.72E+04	2.047E+12
5	Litter from forest subsystem	8.118E+09	J	5.544E+03	4.500E+13
	Renewable input from litter				4.450E+13
	Purchased input from litter				5.025E+11
6	Labor for planting and seedling management	3.829E+06	J	1.700E+06[a]	6.509E+12
7	Labor for harvest and moving	6.966E+06	J	1.700E+06[a]	1.184E+13
8	Mud, feedback from fish pond	6.438E+10	J	*2.562E+04*	1.650E+15
	Renewable feedback in pond-mud				1.182E+15
	Purchased feedback in pond-mud				4.677E+14
9	Soil decrease (organic decrease)	3.166E+10	J	7.250E+04	2.296E+15
10	Oranges before harvest and moving out	7.886E+09	J	*6.642E+05*	5.238E+15
	Oranges after harvest and moving out	7.886E+09	J	*6.657E+05*	5.250E+15
11	Runoff to grassland, geo-potential	4.796E+08	J	2.72E+04	1.304E+13
12	General annual increase of biomass in orchard	5.682E+10	J	*9.219E+04*	5.238E+15
Grassland					
1	Sun	1.316E+13	J	1.00E+00	1.316E+13
2	Evapotranspiration, chemical	1.233E+10	J	2.81E+04	3.465E+14
3	Runoff, geo-potential (from rain directly)	3.674E+07	J	2.72E+04	9.993E+11
4	Runoff, geo-potential (from orchard absorbed in grassland)	3.134E+08	J	2.72E+04	8.525E+12
5	Grass before cutting and moving	2.279E+10	J	*4.256E+03*	9.700E+13
6	Root of grass	6.085E+10	J	*4.256E+03*	2.590E+14
7	Soil improvement (organic increase)	1.618E+10	J	*2.200E+04*	3.560E+14
8	Labor for cutting and moving grass	1.306E+08	J	1.700E+06[a]	2.220E+14
9	Grass after cutting and moving	2.279E+10	J	*1.400 + 04*	3.190E+14
10	Runoff to fish pond, chemical	1.228E+10	J	5.01E+04	6.150E+14
Fish pond					
1	Sun	1.273E+13	J	1.00E+00	1.273E+13
2	Rain, chemical	2.580E+10	J	1.82E+04	4.700E+14
3	Runoff (from grassland), chemical	1.228E+10	J	5.01E+04	6.150E+14
4	Grass for feeding from grassland	2.279E+10	J	1.400 + 04	3.190E+14
	Renewable input in grass				9.700E+13
	Purchased input in grass				2.220E+14
5	Labor for feeding fish	1.306E+08	J	1.700E+06[a]	2.220E+14
6	Labor for mud digging and moving	1.393E+07	J	1.700E+06[a]	2.368E+13
7	Labor for fish harvest and moving	1.393E+07	J	1.700E+06[a]	2.368E+13
8	Fish output	2.864E+09	J	*5.760E+05*	1.650E+15
9	Mud output	6.438E+10	J	*2.562E+04*	1.650E+15

Transformities are relative to the 9.26E+24 sej/a planetary baseline (Campbell, 2000). See Campbell et al. (2005) for sources of most of the transformities. Transformities determined in this study are given in italics.

[a] Lan and Odum (1994).

Table 2 – Emergy input and output of the agro-forest restoration mode and its four subsystems (sej/year)

Item	Forest	Orchard	Grassland	Fish pond	Whole system
Renewable input from sun, rain and wind (R)[a]	1.849E+15	1.239E+15	3.475E+14	4.700E+14	4.531E+15[b]
Runoff from other subsystems (R1)		2.047E+12	8.525E+12	6.150E+14	
Renewable feedback from other subsystems (R2)		1.227E+15		9.700E+13	
Nonrenewable input from soil (N)		2.296E+15			2.296E+15
Service for management (F)	2.088E+13	6.509E+12		2.220E+14	4.951E+14[c]
Service for harvest and moving (F1)		1.184E+13	2.220E+14	4.736E+13	3.552E+13[d]
Purchased feedback from other subsystems (F2)		4.672E+14		2.220E+14	
Yield (Y)	4.500E+13	5.250E+15	3.190E+14	1.673E+15	5.250E+15[e]
Storage increase(ΔQ)	1.870E+15	2.942E+15	3.560E+14		5.026E+15[f]
Ecological economic product (EEP)[g]	1.870E+15	5.250E+15[h]	5.780E+14[i]	1.673E+15	7.358E+15[j]
Yield realized on market (Y_M)[k]	0	2.085E+16[l]	0[m]		
Benefit after market exchange (B)[n]	1.870E+15	2.379E+16	3.560E+14	1.451E+16	4.039E+16[o]

[a] R = evapotranspiration and runoff from rain directly for *A. mangium* forest, orange orchard and grassland; rain chemical for fish pond.

[b] R = sum of the R and R1 of all of the four subsystems, since to the whole system, all of the R1 for the subsystems is coming from the rain in the system area directly.

[c] F = On the system level, it is equal to the labor cost of planting *A. mangium* and orange trees, cutting and moving grass, feeding fish and digging and moving mud to the orchard as fertilizer, while on the subsystem level both the labor cost of cutting and moving grass and digging and moving mud are service costs for harvest and moving.

[d] F1 = labor cost of harvest and moving oranges and fish. Cutting and moving grass to fish pond, and digging and moving mud are costs for harvest and moving on the subsystem level, but they are management costs on system level.

[e] Y = emergy of orange plus the emergy of the fish. Mud and fish are co-products but the mud was feedback to the orange orchard as fertilizer. *A. mangium* litter and grass are also internal flows.

[f] ΔQ of the whole system = R + F = (4.531E+15) + (4.951E+14) = 5.026E+15 sej, equal to soil increase under *A. mangium* forest + biomass increase of orange trees − soil decrease under orchard − litter removed to the orchard + soil increase under grassland − above ground grass before cutting and moving = (1.870E+15) + (5.238E+15) − (2.296E+15) − (4.500E+13) + (3.560E+14) − (9.700E+13) = 5.026E+15 sej; an increase or decrease in soil is assumed to be a co-product of biomass increase in all cases. Litter and grass above ground are assumed to be parts of biomass, thus this emergy has already been accounted for in the soil increase under both *A. mangium* and the grassland. Since the decrease in soil emergy is required for the biomass increase of orange trees it too should be subtracted to avoid double accounting the increase in ΔQ.

[g] EEP = ΔQ + Y.

[h] Equal to the emergy of oranges after harvest and moving + orange tree biomass growth − soil depletion.

[i] EEP for the grassland subsystem = grass after cutting and moving + soil improvement = cutting and moving service + soil improvement = (2.220E+14) + (3.560E+14) = 5.780E+14 sej.

[j] EEP for the whole system = ΔQ + Y = R + N + F + F1 = (4.531E+15) + (2.296E+15) + (4.951E+14) + (3.552E+13) = 7.358E + 15 sej, equal to soil increase under *A. mangium* forest + oranges output − litter removed to orchard + soil increase under grassland-above ground grass before cutting and moving + labor cost for harvest and moving out fish = (1.870E+15) + (5.250E+15) − (4.500E+13) + (3.560E+14) − (9.700E+13) + (2.368E+13) = 7.358E+15 sej; biomass increase and soil increase are assumed to be co-products; litter and grass are part of the biomass increase, so their emergy increase has already been counted in soil increase under both *A. mangium* and grassland. Mud is a co-product with fish; however mud was fedback and accounted for in the orange output. This emergy was counted in the output of the orange orchard subsystem. So the above four items were not counted in the EEP to avoid double accounting.

[k] Y_M = the emergy that can be purchased by the money gained, M_Y, from selling output, Y, on the market.

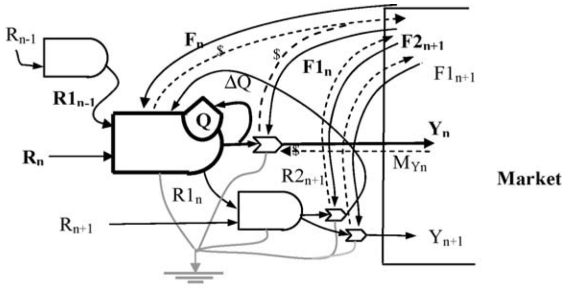
[l] The emergy purchased with the money paid for oranges = (5266.2 kg) × 4/7 × (3.00 yuan/kg)/(4.3 yuan/US$ in 1992)(9.93E+12 sej/US$ 1992 China) = 2.085E+16 sej.

[m] The emergy purchased with the money paid for fish (628.14 kg) × (10 yuan/kg)/(4.3 yuan/US$ in 1992)(9.93E+12 sej/US$ 1992 China) = 1.451E+16 sej.

[n] B = ΔQ + Y_M.

[o] B = ΔQ (gains and losses) + the emergy purchased with the money paid for oranges and fish = (5.026E+15 sej) + (2.085E+16 sej) + (1.451E+16 sej) = 4.039E+16 sej.

Fig. 2 shows the method used to evaluate, separately, both the environmental and economic storages and flows in the linked subsystems. The economic feedback input to the agro-forest restoration system was separated into general management input (F), service for harvest and moving (F1), and feedback support from other subsystems, including both service (F2) and renewable material (R2) inflows. The ecological economic product (EEP) (Fig. 2) was defined as the sum of any increase or decrease in the emergy storages of ecosystem natural capital (ΔQ) plus the emergy of the yield (Y) taken out of the system or subsystem under analysis. Based on this division the emergy yield ratio (EYR) was formulated as the ratio of Y to the sum of purchased inputs (F + F1 + F2) and renewable material inputs (R2) in the case of the orange orchard and fish pond subsystems. The EYR can be used to evaluate the relative efficiency of the economic production processes. Simultaneously, the emergy restoration ratio (ERR) was defined as the ratio of ΔQ, the total change in ecosystem natural capital storages, to the sum of management inputs (F + F2 + R2) to evaluate the relative efficiency of restoration for systems with products or co-products staying within the system and resulting in improvements to the environment, such as soil amelioration and growth of *A. mangium*, orange trees, and grass roots. In cases where the ecosystem capital is diminished, the relative rates of environmental debt accumulation from soil depletion, biomass loss, etc. may be determined from this ratio, which



Emergy Yield Ratio (EYR) = $Y/(F+F1+F2+R2)$

Emergy Restoration Ratio (ERR) = $\Delta Q/(F+F2+R2)$

Ecological-Economic Product (EEP) = $\Delta Q + Y$

Emergy Benefit Ratio = $EEP/(F+F1+F2+R2)$

$B=\Delta Q+Y_M$

$EBE=B/EEP=(\Delta Q+Y_M)/(\Delta Q+Y)$

Fig. 2 – Definition of emergy restoration ratio (ERR), emergy benefit ratio (EBR), and emergy benefit after exchange (EBE). Here we assume that ΔQ is positive (software: Word).

might be more appropriately called the emergy debt ratio (EDR) under these conditions.

The ratio of EEP to the sum of the purchased inputs was defined as the emergy benefit ratio (EBR), which expresses the emergy yield of the system in relation to the emergy feedback from the economy by considering both the change in internal ecological capital and the emergy yield to the larger system. This index is a modification of the EYR to include a correction for increases in internal natural capital stocks, which may be important to accurately evaluate ecological restoration. The gains and losses of natural capital, ΔQ, are determined to minimize double counting. When consumption of internal natural capital exceeds its replacement rate, it is counted in the emergy required for Y so ΔQ cannot be less than 0 in this index.

To determine the benefits of both environmental restoration and the socioeconomic output realized by a system, the benefits to the system after market exchange ($MB = Y \times (Y_M/Y) = Y_M$) must be considered along with the benefits of restoration (ΔQ). Y_M represents the emergy that can be purchased by M_Y, the money received in exchange for the system output, Y. The emergy benefit to the system after selling the output on the market ($B = \Delta Q + MB = \Delta Q + Y \times EER$) can be higher than the EEP for those systems with co-products, some of which stay in place, while others are sold for economic benefit. Accordingly, B is smaller than EEP for systems whose products are sold with an emergy exchange ratio lower than 1 as determined by benefit to the seller. Extending the meaning of emergy exchange ratio (EER) to both ecological and economic benefits as a whole, the ratio of B to EEP is defined as emergy benefit after exchange (EBE), which measures the state of the system as determined by market exchange. If this index is less than 1 more emergy leaves the system than is returned through market exchange. When it is greater than one net emergy, benefit accrues to the system and if it is 1; the emergy exchange is balanced. If all system products are output, then the product of EEP and EBE is equal to the product of EYR and EER, which is the numerator of the emergy index for sustainable development (EISD) (Lu et al., 2002b). EER in the EISD is determined as the emergy benefit to the seller. Based on this equivalence, the product of EEP and EBE was used in the numerator of the EISD to consider ecological effects on sustainable development and to include both environmental and economic benefits in determining the overall efficiency of the system and subsystems under study.

Several emergy indices defined by Odum (1996) and Brown (1997), the emergy yield ratio (EYR), the environmental loading ratio (ELR), the emergy sustainability index (ESI), and the emergy exchange ratio (EER), were used to evaluate, respectively, the ecological economic efficiency of a production process and the net contribution of a product to society, the potential for environmental impacts from human activities, the potential for sustainable development, and the state of the system as measured by market exchange in terms of emergy benefit to the seller.

4. Results and discussions

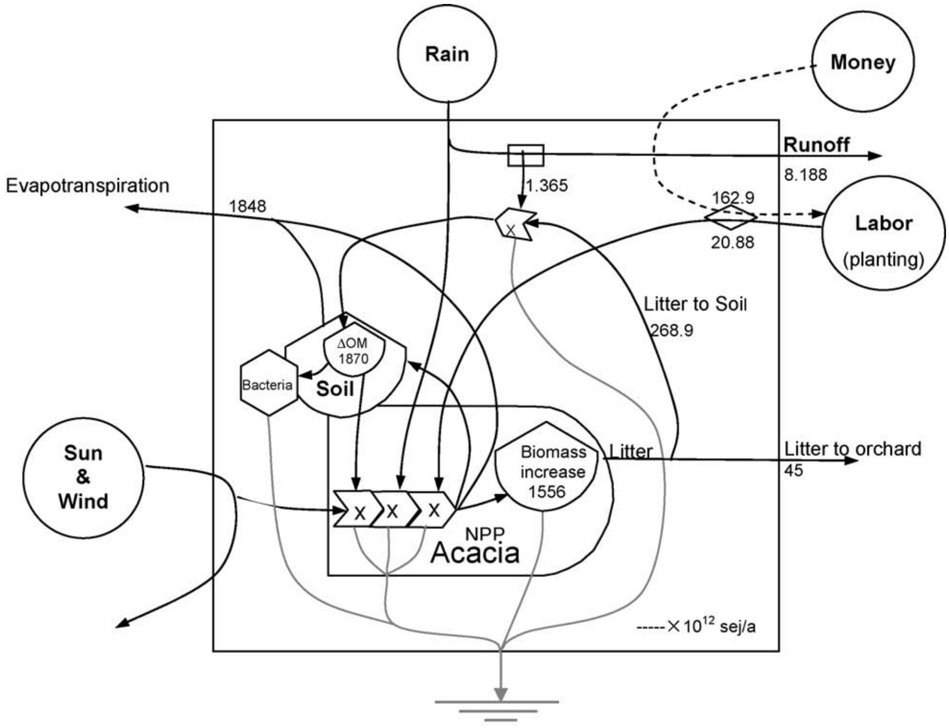
Energy and matter flows of the agro-forest restoration system and its four subsystems were converted into emergy units in Table 1 (see Appendix A for calculations and sources). All of the tools for planting, cutting and moving, such as shovels, pickaxes, barrels, baskets, etc., were supplied by the labors' themselves and the tool depreciations were too small to be counted here. The emergy flows in Table 1 were summed by category and reported in Table 2 and in Fig. 3. The renewable energy base, R, for the whole system is equal to the sum of the chemical potential energy (Gibbs free energy) of evapotranspiration plus the work done on the land by the geo-potential energy of the runoff. These two emergy inflows represent most of the emergy absorbed from the largest planetary emergy input (rainfall) received by this system. Smaller emergy inflows from the planetary co-products of rainfall, such as wind, earth cycle, and direct sunlight are not included in the systems renewable emergy base to avoid double counting inputs. There is no nonrenewable indigenous resource cost in the *A. mangium* forest, grassland, and fishpond subsystems, because of soil amelioration and mud production within them (Peng et al., 2003; Shen et al., 2001).

Based on Table 2 and Fig. 3, some new transformities were calculated and these are marked by italics in Table 1.These are compared with transformities for similar products from other systems in Table 3. In Table 4, a suite of emergy indices was calculated for both the whole system and its subsystems, using functions given by Odum (1996), Brown and Ulgiati (1997), Lu (2002b) and proposed in Section 3 of this paper.

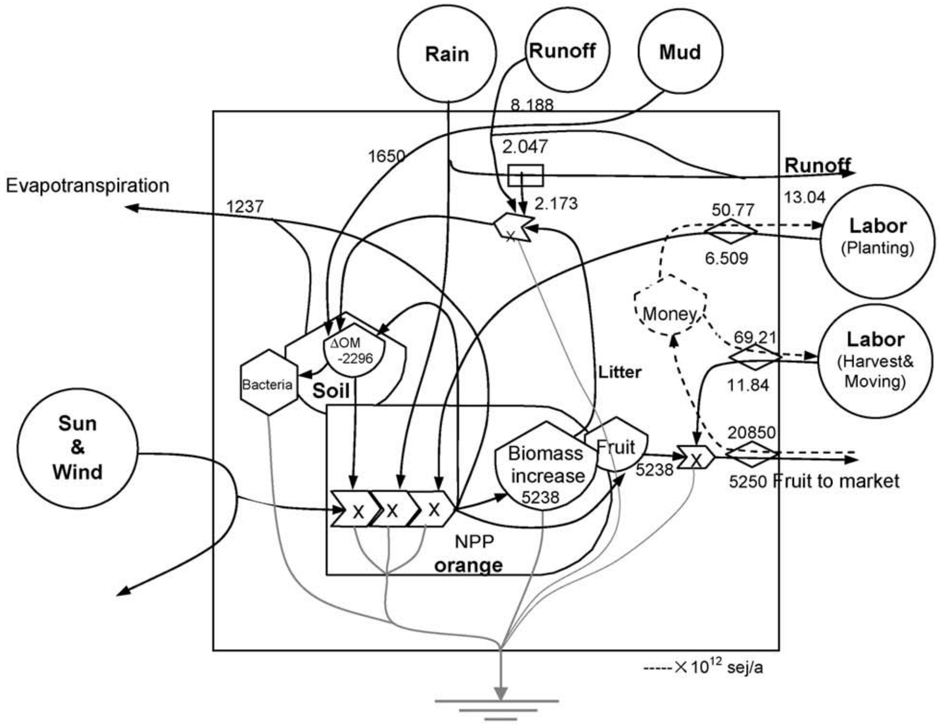
4.1. *Transformity (TR)*

Although transformity (TR) is not usually included in the emergy indices for a system, it is really a very important indicator of the efficiency of the system's production process for an item, and of the quality of the products as well. For the same products, lower TR means higher efficiency of the system's production process for that item.

The TR of soil organic matter under the *A. mangium* forest and in the *P. purpureum* grassland subsystems are just 0.02 and 0.10 times that of a tropical forest in Kenya, and 0.05–0.30 times that of an average transformity for topsoil in the world, which shows the high efficiency of these two restoration subsystems, especially the *A. mangium* forest subsystem, not only for erosion control but also for soil amelioration. Both of these characteristics are essential for pioneer species and for the



(a) Emergy flows of the A. mangium subsystem

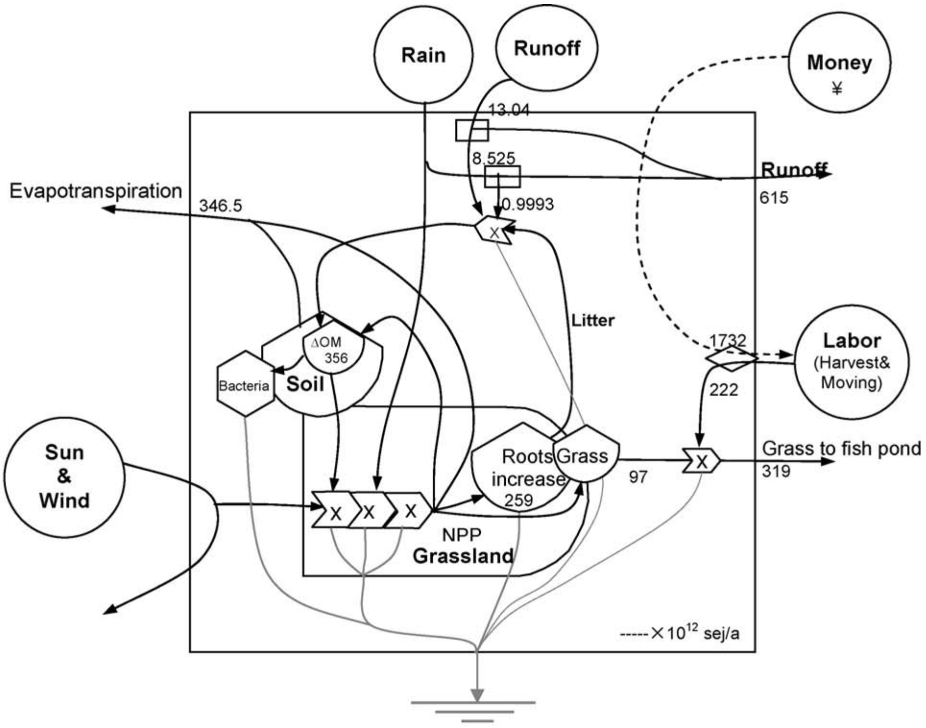


(b) Emergy flows of the orange orchard subsystem

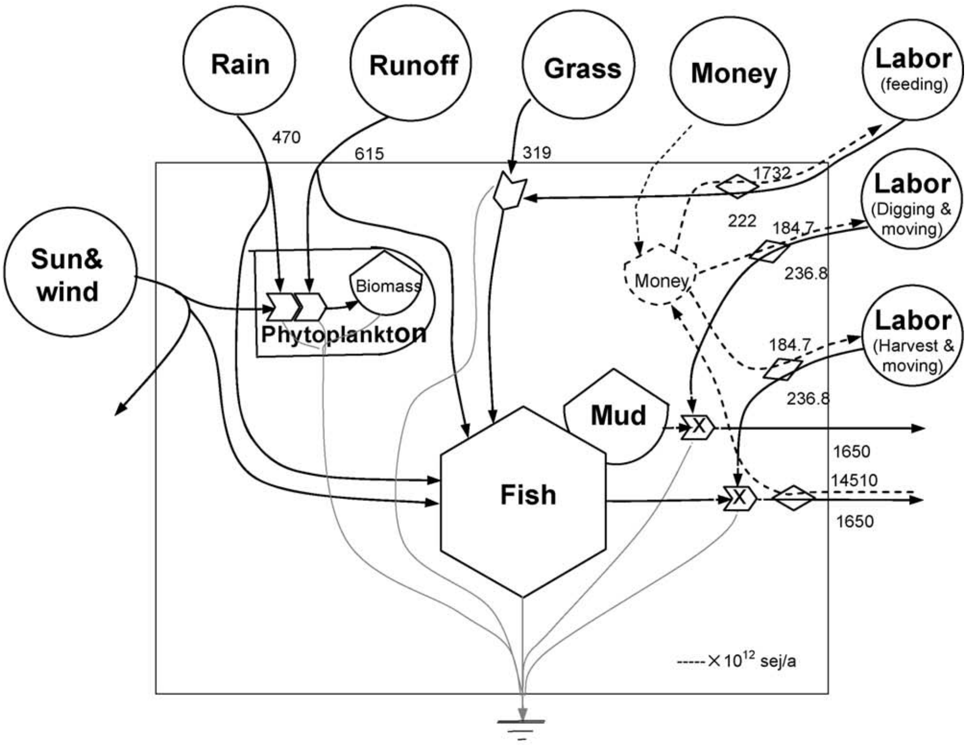
Fig. 3 – Emergy flows of the agro-forest restoration mode on subsystem and system level (software: Word): (a) emergy flows of the *A. mangium* subsystem; (b) emergy flows of the orange orchard subsystem; (c) emergy flows of the grassland subsystem; (d) emergy flows of the fish pond subsystem; (e) emergy flows of the agro-forest restoration system.

rapid restoration of vegetation. The TR of *A. mangium* biomass is just 0.12 times that of a tropical forest in Kenya, and 0.27 times of that of *Albizia lebbek* restoration forest system in Puerto Rico (Odum et al., 2000) showing the fast growth of *A. mangium*, which is another essential characteristic of pioneer species for vegetation restoration.

The TR of *C. reticulata* biomass is higher than forest biomass in both Kenya and the USA, when the oranges produced are

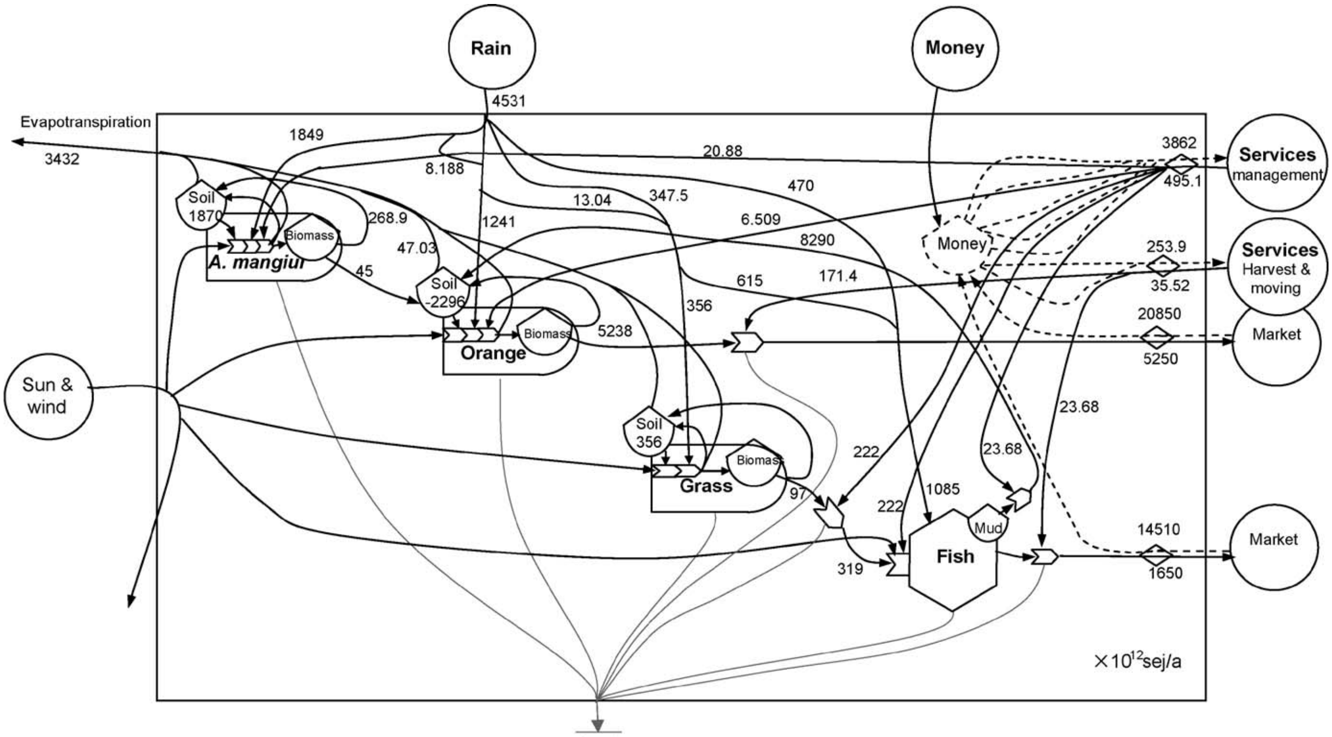


(c) Emergy flows of the grassland subsystem



(d) Emergy flows of the fish pond subsystem

Fig. 3 – (*Continued*)



(e) Emergy flows of the agro-forest restoration system

Fig. 3 – (*Continued*).

taken as a co-product of biomass growth. The TR of harvested oranges in this study is 9.46, 2.56 and 1.74 times the transformity found by Brandt-Williams (1999) for Florida oranges, Odum et al. (1987) for Texas, and Ulgiati et al. (1993) for Italy. The reason why the orange production in our orchard seems to have a low efficiency might be due to the fact that we took the start up cost into consideration and there was no orange harvest in the first 3 years. The soil quality under the orange orchard decreased even with the feedback reinforcement of mud from the fish pond subsystem. Perhaps a fruit species, such as *Dimocarpus longan* which is a low quantity but high quality crop that is very expensive should take the place of oranges in this subsystem. Whether the fruit should be considered as part of the biomass produced or as a co-product of biomass still needs further discussion.

The TR of fish output in this study is 0.46 times the result found by Brown et al. (1992) for fresh water Tilapia culture in Mexico and 0.29 times an average transformity for farm raised fish (Odum et al., 1998). This comparison shows that the fish production subsystem is operating within the

Table 3 – Comparison of transformities from the agro-forest restoration system with similar products from other systems

Item	Emergy Tr (sej/J)	Source	Location
Soil (OM)	3.753E+03 (*A. mangium*)	This study	Subtropical China
	2.200E+04 (grassland)	This study	Subtropical China
	2.18E+05	Cohen (2003)	Tropical Kenya
	7.25E+04	Odum (1996)	Average value Jenny (1982)
Forest biomass	5.544E+03 (*A. mangium*)	This study	Subtropical China
	9.219E+04 (orange trees)	This study	Subtropical China
	4.56E+04	Cohen (2003)	Tropical Kenya
	6.4E+04 (mahogany plantation), 3.9E+04 (secondary succession), 2.023E+04 (*Albizia lebbek* restoration system)	Odum et al. (2000)	Puerto Rico
Orange	6.657E+05	This study	Subtropical China
	7.04E+04	Brandt-Williams (1999)	Florida, USA
	3.817E+05	Ulgiati et al. (1993)	Italy
Vegetable and fruit	2.6E+05	Odum et al. (1987)	Texas. USA
Fish	5.760E+05	This study	Subtropical China
	1.24E+06	Brown et al. (1992)	Tilapia, Mexico
	2.0E+06	Odum et al. (1998)	Arkansas, USA

Table 4 – Indices for the emergy evaluation of the restoration agro-forest restoration system

Index	Function	Forest	Orchard	Grassland	Fish pond	Whole system
Emergy yield ratio (EYR)	$Y/(F+F1+F2+R2)$	2.155	3.066	1.437	2.843	9.894
Emergy restoration ratio (ERR)	$\Delta Q/(F+F2+R2)$	89.559	1.730		0	9.472
Emergy benefit ratio (EBR)	$EEP/(F+F1+F2+R2)$	89.559	3.066	2.604	2.843	13.867
Environmental loading ratio (ELR)	$(F+F1+F2+N)/(R+R1+R2)$	0.011	1.127	0.624	0.416	0.624
Emergy sustainability index (ESI)	EYR/ELR[a]	190.848	2.720	2.304	6.840	15.860
Emergy exchange ratio (EER)	Y_M/Y		3.971		8.794	
Emergy benefit in exchange (EBE)	$(\Delta Q+Y_M)/(\Delta Q+Y)=B/EEP$	1.000	4.531	0.616	8.673	5.489
Emergy index for sustainable development (EISD)	$(EBR\times EBE)/ELR$	7930.81	12.326	2.572	59.326	122.016

[a] Brown and Ulgiati (1997).

expected range of efficiencies for farm raised fish and that fish from the restoration mode should be competitive in local markets.

4.2. *Emergy yield ratio (EYR) and emergy restoration ratio (ERR)*

EYR is the fundamental emergy indicator of the yield compared to inputs other than local, which gives a measure of the ability of the process to exploit local resources (Brown and Ulgiati, 1997). The emergy restoration ratio (ERR) is proposed above for the inclusion of ecological benefits from the restoration process. As a pure reforestation system, the *A. mangium* subsystem gets 99% of its environmental emergy input from indigenous sources, especially the chemical potential of evapotranspiration, whereas, only 1% of the emergy input comes from the human service needed to plant trees and manage the forest at the beginning (Table 1). As a result the EYR (2.155) and the ERR (89.559) are high (Tables 2 and 4), even though the majority of the net increase in biomass and soil amelioration stayed within this subsystem as storage, and only a small part (14.34%) of the litter produced was moved to the orchard subsystem by gravity and wind. All of the other three subsystems may be considered as agriculture or aquaculture production systems and as such they all have EYRs greater than 1, indicating a positive net benefit to the economy. Among them, the EYR of the orange orchard subsystem is the highest one. This system produces fruit for local markets using renewable inputs of runoff, litter from the *A. mangium* subsystem and a feedback of mud from the fish pond subsystem. The EYR of the grassland subsystem is the lowest one among the four subsystems due to the high labor cost for cutting and moving grass to the fish pond. The ERR of the orange orchard subsystem is lower than its EYR, because the net benefit of orange tree biomass growth is in part cancelled by a decline in soil organic matter. The ERR of the grassland subsystem was not determined since there are almost no purchased inputs for the restoration of this subsystem, with only one day's labor planting cost in 1986. Since all of the products of the fish pond system are removed as output (fish and mud), the ERR of the fish pond subsystem is 0. Both the ERR and EYR for the whole system are large (9.47 and 9.89) because it benefits from the production of agricultural and aquaculture products as well as from the building of internal ecosystem storages in some of the subsystems.

4.3. *Emergy benefit ratio (EBR)*

EBR was defined as the ratio of the ecological economic product (EEP) to the sum of purchased inputs to the production system. It measures the ecological and economic efficiency of the emergy applied in a production system as a result of human behavior. In the *A. mangium* subsystem the EBR is equal to the ERR, since biomass and soil improvement are considered to be co-products, kept in the place, and the litter is moved out of the system by natural processes without any additional human service cost. In the orange orchard and grassland subsystems, the EBR is greater than the EYR, since both subsystems have internal increases in natural capital and exported products. The orange fruit harvested is an economic product and the biomass increase of orange trees gives a net positive change in natural capital storages in this subsystem. In the fishpond subsystem the EBR is equal to EYR, since all of the products of this subsystem were moved out as output. In the grassland subsystem, the EBR is higher than EYR, since only part of the increase in grass biomass was cut and moved out, while increases in root biomass and soil improvement are co-products, but only the largest is counted as an improvement to ecosystem capital storages. Even though the *A. mangium* subsystem is without any direct economic output, the EBR of this subsystem is 29.21 to 34.39 times that of the other three subsystems, as a result of low human intervention. The relationship between the EYR and the EBR will vary somewhat depending on how system products are classified. Certain products might legitimately be considered as both increases of system natural capital and as subsystem yield. In each case, we have stated our assumptions above.

4.4. *Environmental loading ratio (ELR)*

ELR was defined as the ratio of purchased input and nonrenewable indigenous emergy use to the renewable environmental emergy use, and it indicates the pressure on the environment from human activities. Since the purchased inputs to the orange and fish pond subsystems were separated into an indigenous renewable part (R2), and nonrenewable part (F2), R2 was added to R in the denominator of the ELR expression because it came from locally renewable resources. There are two kinds of production processes that have a low ELR. The first type has few purchased inputs, such as the *A. mangium* forest subsystem (Tables 2 and 4), and the second type has a large local renewable input either naturally (R) and/or artificially (R2) by subsidy from the outside, such as the fish pond and grassland subsystem (Tables 2 and 4).

4.5. *Emergy sustainability index (ESI)*

The target of sustainable development is focused on getting the highest yield ratio versus the lowest environmental loading, i.e. highest ESI (Brown and Ulgiati, 1997). With only about 14.34% of biomass moved out as yield, but very low labor cost, the EYR of the *A. mangium* forest is lower than that of the orchard and fishpond subsystem, but higher than that of grassland. However, the ESI of the *A. mangium* subsystem is still 27.90–82.83 times that of the other three subsystems, because human intervention in this subsystem is low. The grassland has the lowest sustainability among the four subsystems due to the high labor cost of cutting and moving the grass. To improve the sustainability of this system, duck breeding might be introduced into the grassland subsystem, based on the fact that ducks can eat the grass without human service and their dejecta is great forage for fish, while the swimming action of the duck's feet can improve oxygen content in the pond water both of which are evidently good for fish breeding (Zheng and Deng, 1998; Lu et al., 2002a).

4.6. *Emergy exchange ratio (EER) and the emergy benefit after exchange (EBE)*

Emergy exchange ratio (EER) is the emergy that can be purchased by the money or other reward received from selling trading or moving a unit of product out of the system to the emergy contained in that quantity of product (Odum, 1996). It is an indictor of the relationship of the system under study to the market. An EER lower than 1 means the system lost wealth in the trade, as seen in the grassland subsystem, where all of its above ground biomass was moved out with high labor cost and without any feedback to the subsystem as a reward. In contrast, an EER greater than 1 means the system got excess wealth through trading, as demonstrated by the orchard and fish pond subsystems which received 3.97 and 8.79 times the emergy in oranges and fish upon trading. We modified the EER to include the effects of changes in the emergy of natural capital within the system as well as the emergy purchasing power received from economic products. This new ratio is the emergy benefit after exchange ($\mathrm{EBE} = (\Delta Q + \mathrm{MB})/\mathrm{EEP} = (\Delta Q + Y \times \mathrm{EER})/(\Delta Q + Y)$) and it represents the net benefit received by a system as a consequence of economic production and trade. The EBE of the fishpond subsystem (8.673) was the highest one of the two systems that produced economic products, since the pond fish were sold with a high EER. The EBE of the orchard subsystem is higher than its EER, since the biomass of orange trees was left in place to provide environmental services which exceed the declines in soil productivity. The grassland subsystem has the lowest EBE due to the large removal of biomass without remuneration from a market. Since the increase in soil is assumed to be a co-product of biomass increase in storage change of natural resource, with only a small fraction of the natural systems co-products moved out by natural forces while all of the soil increase stayed in the place, the EBE of *A. mangium* forest is equal to 1.

4.7. *Emergy index for sustainable development (EISD)*

The product of EYR and EER is the benefit ratio (Y_M/F) of the investment (F) realized by the system under study after the products of the system are sold or traded. EYR gives the benefit ratio (Y/F) for the larger system without considering the emergy exchange when the products of the system are sold. With the fluctuation of market price, EER is not equal to 1 most of the time, and the reward obtained by a system after trading is the real benefit realized by that system. Based on this consideration, the emergy index for sustainable development (EISD) (Lu et al., 2002a), was introduced and it is further developed in this paper.

After taking both ecosystem storages and market trading into account by substituting EBE for EER, and EEP for EYR in the numerator of the expression for EISD, the sequence of the four subsystems using the EISD is the same as that found using the ESI, but the index values and the percentage differences among them changed. The EISD of the agro-forest restoration system is 7.69 times the ESI, as the result of considering the effects of changes in internal ecological storages and external emergy exchange in the market. The EBE and EISD show that there is the potential to improve the emergy exchanges realized by both the orange and fish pond systems where high quality products were sold on the market at the same price as poorer quality agricultural products with high pesticide contamination. Short-term benefits might be obtained by switching to a fish species, such as *Siniperca chuatsi* B., and a fruit tree species, such as *Dimocarpus longan*, which have a high EER (benefit to the seller) when sold on the market (Lu et al., 2002a,b).

For most ecological economic systems the ESI and EISD may get different numerical results, especially for those processes and systems where some of the products are sold with EER unequal to 1 and others remain within the system to augment natural capital. Further research is needed to determine if the ESID and the ESI always result in the same ranking of relative sustainability. In any case, the EISD offers additional information for decision makers on the net emergy benefit to the system from economic exchange and the effects of internal ecosystem changes that is not available from the ESI.

5. Conclusions

Introducing principles and methods of ecological engineering to improve the efficiency of material and energy use can bring great benefits to the ecosystem as well as to the economy. In some underdeveloped areas, people have difficulty supporting themselves and their families as a result of the poor environment. In such cases, people have no money to pay for restoring the vegetation. The simple and inexpensive agro-forest restoration mode produces superior benefits in ecological restoration and economic yield, and often becomes the only way that the poor in the low subtropical region of China can afford environmental improvements. Our results indicate that the *A. mangium* forest–orchard–grassland–fish pond agro-forest system is an excellent restoration system, although options for further optimization were suggested in this paper. This restoration mode and its variations might be used to restore vegetation in other places, especially on hillside areas that will allow the full use of runoff and pond-mud to support ecological productivity.

To make clear the ecological and economic benefits of vegetation restoration processes, and to fill the need for evaluating sustainable development alternatives, a new axiology and its corresponding methods are needed. Emergy synthesis is a valuable tool for determining value and for evaluating and identifying sustainable interfaces of the environment with the social economy. However, all such analyses should be carried out on multiple scales to demonstrate how net benefits and sustainability change with position in the hierarchical organization of environmental systems. Further development of the emergy methodology, including a clearer understanding of the rules to define products and co-products on multiple scales and the integration of emergy studies with more traditional ecological studies, points the way toward more robust results. For example, multiple-level studies were essential for further optimization of the system under study here. Analysis of the subsystems can shed light on the connectivity among the subsystems and on the strength and weaknesses of internal reinforcing feedbacks within the system. Our investigation of ecological effects within the mother system and the market exchange of system products resulted in some detailed suggestions for further optimization of the agro-forest restoration system, such as changing the fruit and fish species, and introducing ducks into the grassland.

The most significant result of this work for emergy synthesis is the introduction of several new emergy indices. The new indices and the reasons for proposing them are as follows: (1) The ERR–EDR index was formulated to show the effectiveness of restoration actions and environmental debt accumulation per unit of purchased input. (2) The EEP was defined to consider both the change in the emergy of internal natural capital and the emergy yield of output products as the net result of human activities. (3) EBR was formulated to show the change in the net emergy of output products and ecosystem natural capital as a function of an additional unit of purchased inputs. (4) The EBE was designed to show the net emergy effects of an exchange on the system that sells its products, including the emergy that can be purchased with the money received from a product and the overall change in the emergy of natural capital within the system. These indices along with the further development and modification of the EISD provide several new tools for environmental managers that may make the subtleties of emergy synthesis clearer and allow better decisions to be made. Further development of these indices could make the interpretation of the results of emergy evaluation on different scales clearer.

Acknowledgments

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Appendix A

Calculations and references for Table 1 are given in Table A.1.

Table A.1

Item	Raw unit per year	References
A. mangium forest		
Sun		
Average data in J/m^2/a, measured by Heshan Restoration Station over the past 20 years	4.388E+9	Ding et al. (1995)
Land area in m^2	1.3E+4	
Energy (J per year); product of all above	5.704E+13	
Evapotranspiration		
Evapotranspiration in m per year	0.915	Yan et al. (2002)
Area in m^2	1.3E+4	
Water density in kg/m^3	1.00E+03	
Free energy of water in J/kg	4.94E+03	
Chemical energy (J per year); product of all above	6.576E+10	
Runoff		
Runoff in m per year	3.938E−02	
Land area in m^2	13000	
Altitude difference in m (average altitude minus the lowest altitude)	$(80+60)/2-60=10$	
Water density in kg/m^3	1.00E+03	
Gravity in m/s^2	9.8	
Geo-potential Energy (J per year); product of all above	5.017E+07	

Table A.1 – *Continued*

Item	Raw unit per year	References
Labor cost for planting		
Number of trees	2116	
Number of holes every labor dig per day	80	
Number of trees every laborer planted into the ready holes per day	400	
Working time per day (hours/day)	8	
Energy cost per hour (kcal)	1.04E+02	
J/kcal	4186	
Energy	1.105E+08	((2116/80) + (2116/400)) × 8 × (1.04E+02) × 4186 = 1.105E+08
Tree age	9	
Annual labor cost for planting (J)	1.228E+07	(1.105E+08)/9 = 1.228E+07
Biomass increase		
Land area in m^2	13000	
General annual increase of trunk in g/m^2	701.22	Ren et al. (1995)
Free energy of trunk in J/g	18746	Ren et al. (1995)
General annual increase of branch in g/m^2	155	Ren et al. (1995)
Free energy of branch in J/g	18327	Ren et al. (1995)
General annual increase of leaf in g/m^2	44.788	
Free energy of leaf in J/g	20151	
General annual increase of root in g/m^2	252.44	
Free energy of root in J/g	18649	
Energy (J per year); sum of energy in above parts	2.807E+11	
Litter staying in the *A. mangium* forest		
General annual increase of litter in g/m^2	1114	
Area of *A. mangium* forest in m^2	13000	
Free energy of litter, in J/g	3349	
Energy of litter staying in *A. mangium* forest per year	4.850E+10	
General annual flux of litter to orchard in g/m^2 litter moved to orchard naturally	278.6	
Area of orchard m^2	8700	
Free energy of litter, in J/g	3349	
Energy of litter moved to orange orchard naturally, in J	8.118E+09	
Runoff to orchard		
In m^3 per year	3.938E−02 × 13000	
Altitude in m	60	
Water density in kg/m^3	1.00E+03	
Gravity in m/s^2	9.8	
Geo-potential energy (J per year); product of all above	3.010E+08	
Soil improvement		
Area of *A. mangium* forest in m^2	13000	
General annual increase of organic matter above 100 cm depth, in g/m^2	1695	
Free energy of organic, in kcal/g	5.4	
J/kcal	4186	
Energy of general annual increased organic matter, in J	4.982E+11	
Orange orchard		
Sun		
Average data in J/m^2 a, measured by Heshan Restoration Station in past 20 years	4.388E+9	Ding et al. (1995)
Land area in m^2	8700	
Energy (J per year); product of all above	3.818E+13	
Evapotranspiration		
Evapotranspiration in m per year	1.024	Odum et al. (1998)
Area in m^2	8700	
Water density in kg/m^3	1000	
Free energy of water in J/kg	4.94E+03	
Chemical energy (J per year); product of all above	4.401E+10	

Table A.1 – *Continued*

Item	Raw unit per year	References
Runoff		
Runoff from rain directly in m per year	1.250E−01	
Land area in m^2	8700	
Altitude variety in m (average altitude minus the lowest altitude)	(60 + 45)/2 − 45 = 7.5	
Water density in kg/m^3	1.00E+03	
Gravity in m/s^2	9.8	
Geo-potential energy (J per year); product of all above	7.991E+07	
Runoff from *A. mangium* forest in m^3 per year	3.938E−02 × 13000	
Altitude variety in m	60 − 45 = 15	
Water density in kg/m^3	1.00E+03	
Gravity in m/s^2	9.8	
Geo-potential energy (J per year); product of all above	7.527E+07	
Litter		
From *A. mangium* forest in g/m^2	278.6	
Land area in m^2	8700	
Dry litter/ wet litter	0.2	
Free energy of dry litter in kcal/g	4	
J/kcal	4186	
Energy (J per year); product of all above	8.118E+09	
Labor cost for planting		
Number of trees	513	
Number of holes every laborer digs per day	80	
Number of trees every labor planted into the ready holes per day	400	
Working time per day (hours/day)	8	
Energy cost per hour (kcal)	1.04E+02	
J/kcal	4186	
Energy	2.680E+07	
Tree age	7	
Annual labor cost for planting (J)	3.829E+06	
Labor cost for harvest and moving orange		
Number of labor hired	2	
Working hours	8	
Energy cost per hour (kcal)	1.04E+02	
J/kcal	4186	
Annual labor cost for harvest and moving orange (J)	6.966E+06	
Mud		
Feedback from fish pond in kg	25650	
g/kg	1000	
Free energy of mud in J/g	2510	
Energy (J per year); product of all above	6.438E+10	
Soil decrease in fertility		
Area of orange orchard in m^2	8700	
General annual decrease of organic matter above 100 cm depth, in g/m^2	161	
Free energy of organic, in kcal/g	5.4	
J/kcal	4186	
Energy of general annual decreased organic matter, in J	3.166E+10	
Orange		
Fruit age	4	
Tree age	7	
General output in kg per year after planting	5266.2 × 4/7 = 3.009E+03	
g/kg	1000	
Free energy of orange in J/g	2620	USDA Nutrient Data Laboratory "Food Composition and Nutrition." http://www.nal.usda.gov/fnic/cgi-bin/nut_search.pl
Energy (J per year); product of all above	7.884E+09	

Table A.1 – *Continued*

Item	Raw unit per year	References
Runoff to grassland		
in m^3 per year	3.938E−02 × 13000 + 1.250E−01 × 8700	
Altitude in m	45	
Water density in kg/m^3	1.00E+03	
Gravity in m/s^2	9.8	
Geo-potential energy (J per year); product of all above	4.796E+08	
Biomass increase of fruit trees		
General annual increase of trunk in g/tree	550.52	
Free energy of trunk in J/g	18746	Ren et al. (1995) (use the data of A . . . trees)
General annual increase of branch in g/m^2	1674.27	
Free energy of branch in J/g	18327	Ren et al. (1995) (use the data of A . . .. trees)
General annual increase of leaf in g/tree	218.62	
Free energy of leaf in J/g	20151	Ren et al. (1995) (use the data of A . . . trees)
General annual increase of root in g/tree	527.35	
Free energy of root in J/g	18649	Ren et al. (1995) (use the data of A . . . trees)
Number of trees	513	
Litter in g/m^2	977.4	
Land area in m^2	8700	
Dry litter/ wet litter	0.2	
Free energy of dry litter in kcal/g	4	
J/kcal	4186	
Energy (J per year); sum of energy in above parts	5.682E+10	
Grassland		
Sun		
Average data in J/m^2/a, measured by Heshan Restoration Station over the past 20 years	4.388E+9	Ding et al. (1995)
Land area in m^2	3000	
Energy (J per year); product of all above	1.316E+13	
Evapotranspiration		
Evapotranspiration in m per year	8.321E−01	
Area in m^2	3000	
Water density in kg/m^3	1000	
Free energy of water in J/kg	4.94E+03	
Chemical energy (J per year); product of all above	1.233E+10	
Runoff		
Runoff from rain directly in m per year	3.782E−02	
Land area in m^2	3000	
Altitude variety in m (average altitude minus the lowest altitude)	(45 + 25)/2 − 25 = 10	
Water density in kg/m^3	1.00E+03	
Gravity in m/s^2	9.8	
Geo-potential energy (J per year); product of all above	3.674E+07	
Runoff from orchard in m^3 per year	3.938E−02 × 13000 + 1.250E−01 × 8700	
Altitude difference in m	45 − 25 = 20	
Water density in kg/m^3	1.00E+03	
Gravity in m/s^2	9.8	
Geo-potential Energy (J per year); product of all above	3.134E+08	
Biomass		
Grass (above ground) in g/m^2	2980	
Dry/wet	0.145	
Free energy in J/ g	1.758E+04	
Land area in m^2	3000	
Energy (J per year); product of all above	2.279E+10	

Table A.1 – *Continued*

Item	Raw unit per year	References
Root (under ground) in g/m^2	4455	
Dry/wet	0.259	
Free energy in J/g	1.758E+04	
Land area in m^2	3000	
Energy (J per year); product of all above	6.085E+10	
Labor cost for cutting and moving grass		
Number of labor hired	1	
Working hours	300	
Energy cost per hour (kcal)	1.04E+02	
J/kcal	4186	
Annual labor cost for cutting and moving grass (J)	1.306E+08	
Runoff to fish pond in m^3	3.938E−02 × 13000 + 1.250E−01 × 8700 + 3.782E−02 × 3000	
Water density in kg/m^3	1000	
Free energy of water in J/kg	4.94E+03	
Energy (J); product of all above	1.228E+10	
Fish pond		
Sun		
Average data in J/m^2 a, measured by Heshan Restoration Station in past 20 years	4.388E+09	Ding et al. (1995)
Land area in m^2	2900	
Energy (J per year); product of all above	1.273E+13	
Rain		
Land area in m^2	2900	
Rain (average) in m per year	1.801	
Water density in kg/m^3	1000	
Free energy of water in J/kg	4.94E+03	
Energy (J); product of all above	2.580E+10	
Runoff		
Runoff from forest, orchard and grassland in m^3	3.938E−02 × 13000 + 1.250E−01 × 8700 + 3.782E−02 × 3000	
Water density in kg/m^3	1000	
Free energy of water in J/kg	4.94E+03	
Energy (J); product of all above	1.228E+10	
Labor cost for feeding fish		
Number of labor hired	1	
Working hours	300	
Energy cost per hour (kcal)	1.04E+02	
J/kcal	4186	
Annual labor cost for harvest and moving (J)	1.306E+08	
Labor cost for digging and moving mud		
Number of labor hired	4	
Working hours	8	
Energy cost per hour (kcal)	1.04E+02	
J/kcal	4186	
Annual labor cost for digging and moving mud (J)	1.393E+07	
Labor cost for harvest and moving fish		
Number of labor hired	4	
Working hours	8	
Energy cost per hour (kcal)	1.04E+02	
J/kcal	4186	
Annual labor cost for harvest and moving fish (J)	1.393E+07	
Fish		
Output in kg	628.14	
g/kg	1000	
Free energy of fish in J/g	4560	
Energy (J); product of all above	2.864E+09	
Mud		
Output in kg	25650	
g/kg	1000	
Free energy of mud in J/g	2510	
Energy (J); product of all above	6.438E+10	

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