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# Bamboo vs. crops: an integrated emergy and economic evaluation of using bamboo to replace crops in south Sichuan Province, China

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## Abstract

Based on long-term monitoring conducted in Chang-ning county, a pilot site of the ‘Grain for Green Program’ (GFGP), an integrated emergy and economic method was applied to evaluate the dynamic ecological-economic performance of 3 kinds of bamboo systems planted on sloping farmland. The results confirmed the positive effects of all 3 kinds of bamboo systems on water conservation and soil erosion control. The benefits gained progressively increased during the first 8 years after conversion, going from 4639 to 16127 EMyuan/ha/yr on average. All three bamboo plantations were much more sustainable than common agricultural crops planted on sloping land (CP) on both the short and long-term scales with their Emergy Sustainability Index (ESI) and Emergy Index for Sustainable Development (EISD), respectively, being 14.07-325.71 and 80.35-265.80 times that of CP. However, all 3 bamboo plantations had a Net Economic Benefit (NEB) less than that of CP during the first 8 years after conversion. Even with the government-mandated ecological compensation applied, the annual $\mathrm{NEB}_{\mathrm{EC}}$s of the *Bambusa rigida* (BR) and *Phyllostachys pubescense* (PP) plantations were, respectively, 3922.03 and 7422.77 yuan/ha/yr lower than the NEB of CP. Emergy-based evaluation of ecosystem services provides an objective reference for applying ecological compensation in strategy-making, but it cannot wholly solve the economic viability problem faced by all bamboo plantations. Inter-planting annual herbs or edible fungus, such as *Dictyophora echinovolvata*, within bamboo forests, especially in young bamboo plantations, might be a direction for optimizing bamboo cultivation that would improve its economic viability.

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**Keywords**

grain for green program; emergy; bamboo; soil erosion; ecological compensation

## 1. Introduction

The second Chinese national survey of soil erosion based on remote sensing analysis showed that in the last decade of the 20th century the eroded area was 3.56 million km$^2$, which occupied about 37.1% of the total land area of China (Liu, 2002). To address this problem, in 1999, China launched the ecological engineering 'Grain for Green Program' (GFGP, also called the sloping land conversion program) and it has become one of the largest ecological restoration programs in the world. The goal of the program is to reduce soil erosion and increase vegetation coverage by replacing sloping farmland with easily planted forests (Li et al., 2016). By the end of 2013, under this program the forest area in China had been increased by approximately 27.67 million ha, at a cost of approximately 35.88 billion US$ (Guo et al., 2014; Wang et al., 2017). The area of bamboo forest in China increased 43% during this period going from 4.21 million ha in 1998 to 6.01 million ha in 2013 (Yuen et al., 2017). The reason behind this quickly extending is the superior adaptability, fast growth, and economic viability of bamboo (Jiang, 2007; Chen et al., 2008; Song et al., 2011).

Considering the large spatial scale and the tremendous number of participants and considerable economic investment made in GFGP, many evaluations of its ecological or economic performance at different scales have been performed over the past ten years. However, a suite of different and sometimes conflicting results have been obtained (Weyerhaeuser et al., 2005; Deng et al., 2012; Xu et al., 2007; Wang & Maclaren, 2012; Li et al., 2016). One of the main reasons behind these differences is that the same government-mandated ecological compensation standard (3450 yuan/ha/yr from 2003 to 2010) was applied to a large area with significantly different spatial distributions of environmental resources (Kong, 2007; Wu, 2007), without considering the effects of deflation/inflation on compensation. In addition, in practice, agricultural productivities and the ecological-economic properties of the specific GFGP modes are variable making a single value for ecological compensation impractical (Liang et al., 2006; Wang et al., 2007). Although bamboo forests are rapidly growing alternatives for use in the GFGP, the ecological-economic characteristics of using bamboo to replace crops on sloping land has been rarely studied (Song et al., 2011; Yuen et al., 2017).

Besides, most of the past research has been snapshot comparisons focused on particular processes such as soil erosion control, water provision, soil fertility maintenance, carbon sequestration, afforestation techniques, economic performance, *etc.* (Jia et al., 2004; Liang et al., 2006; Wang et al., 2007; Qi et al., 2013; Cheng et al., 2015). While GFGP is a continuing, long-term project, integrated and comparable evaluations of both short-term economic and long-term ecological performances of these restoration modes is lacking, but urgently needed for mode selection, optimization, and adaptive management (Jia et al., 2014, Wang et al., 2017).

Based on long-term monitoring conducted in Chang-ning County, a pilot site of the GFGP, we applied an integrated emergy and economic evaluation to explore the ecological-economic dynamics of three kinds of bamboo forest plantation systems compared to a common crop system found in the region. A suite of questions was of particular interest, *i.e.*, whether these bamboo systems can reduce soil erosion from sloping agricultural systems? If yes, does this environmental benefit lead to better ecological economic performance of the bamboo plantation systems compared with a common crop system planted on sloping land? What is the difference among the three bamboo systems and the common crop system, and are there any sensitive points that are worth paying attention to for further optimization of these systems? Is the ecological compensation scheme implemented well-matched with the actual ecological economic properties of these modes? If not, what kinds of adjustments should be made?

## 2. Study sites and methods

### 2.1. Location and study sites

The experimental area was located in Chang-ning County (104°44′-105° 03′ E, 28° 25′-28° 48′ N) (see Fig.1.), Sichuan Province, and it is controlled by mid-subtropical monsoon weather, with annual average sunshine of 1,212 hours, an annual average temperature of 18.3°C, with the maximum temperature going up to 40.7°C and the minimum temperature down to −4.2°C. This area has an annual average rainfall of 1104 mm and rainfall is concentrated in the rainy season from April to September. The annual frost free period is 358 days. As a pilot site of the GFGP to replace crops on sloping ground with bamboo forests, the area of bamboo forest plantations increased from 21,402 ha in 2000 to 48,713 ha in 2016, which accounts for 82.6% of the total forest area in Chang-ning County. In 2016, over 84% of the bamboo plantations were dominated by 3 species, *i.e. Bambusa rigida* (40.39%), *Phyllostachys pubescens* (33.00%), and *Pleioblastus amarus* (10.81%).

The bamboo forest plantations examined are representative of all three major types of bamboo forests, *i.e.*, monopodial (runner rhizomes), sympodial (clumping rhizomes), and mixpodial (characteristics of both clumping and runner rhizomes) bamboo forests. Also, an important factor in the evaluation is that the economic utilities of the three dominant species planted are different, i.e., the culm of *Bambusa rigida* (BR) is widely used as the raw material for paper-making; *Pleioblastus amarus* (PA) is mainly planted for its edible bamboo shoot, while both the bamboo shoots and culms of *Phyllostachys pubescense* (PP) are generally used as a vegetable, decorative material, farm tools *etc.*

Both 3 and 8 year-old plantations were investigated to explore the dynamic ecological-economic performance of the three types of bamboo forest plantations, considering that the economic investment cycles are 3 years for *Bambusa rigida and Pleioblastus amarus*, and 8 years for *Phyllostachys pubscense.* Perhaps not coincidentally, 8 years is also the period of ecological compensation for the GFGP, after which the ecological economic characteristics of these forests are expected to yield benefits that are at least as great as those from the agricultural systems commonly used on sloping land.

### 2.2. Experimental methods

In order to explore the ecological economic effects of using bamboo to replace crops, 9 bamboo forest plantations were selected as the treatment group with 3 replicates employed for each of the three kinds of bamboo plantations. Simultaneously, a common crop system on sloping areas in Chang-ning county, i.e. the corn-sweet potato (CP) system, which plants corn from March to July, and sweet potato from June to November, was chosen as the control, for which we also employed 3 replicates. Detailed information on these study sites is given in Table 1.

Four catchment areas (20×20 $m^2$) were set up to monitor surface runoff and soil erosion from the bamboo and agricultural systems, with a water pool (25000 $m^3$) built at the foot of each catchment area to collect the surface runoff and eroded materials. After a rain event, the depth of water in the pools was measured and water samples were taken to measure the soil content using filtration methods. The height (H), diameter at breast height (DBH), and canopy area (CA) of all bamboo stands in the study sites were measured to estimate biomass. In addition, fifteen standard bamboo plants were harvested and separated into 3 parts (culm, branch and leaf) for weighing. Then, 3 equations were set up to estimate the aboveground biomass based on the observed relationship between biomass and DBH, as follows:

$$W_{br}=0.142 \times DBH^{2.15}(R^2=0.98)$$

$$W_{pp}=0.143 \times DBH^{2.01}(R^2=0.88)$$

$$W_{pa}=0.199 \times DBH^{1.819}(R^2=0.94)$$

The biomass of the crops (corn and sweet potato) was measured by the whole harvest method.

Nine, 20 cm depth soil cores were collected from each study site using core tubes (4 cm in diameter) and pooled into 3 samples. Then, the concentration of soil organic matter (SOM) was measured by the potassium dichromate oxidation method. The meteorological data, *e.g.*, solar radiation, rainfall and wind speed, were taken by the bureau of meteorology of Chang-ning County, while the economic data, *e.g.*, corn prices, bamboo shoot and bamboo culm prices, the input of labor and seedlings *etc.*, were collected from 30 Chang-ning county farmers chosen randomly in our investigation.

### 2.3. Emergy evaluation

Based on the biogeochemical cycle of the Earth, emergy evaluation provides a long-term, large-scale, donor-side valuation method that can quantify all kinds of energy, material and monetary assets, in a common unit, solar emjoules (sej) (Odum, 1983; 1996). After over 3 decades' of development, improvement and application, emergy synthesis has become a mature ecological-economic evaluation approach to evaluate systems on all time and space scales (Odum, 1971; 1988; 1996; 2007), and it has been widely applied in the evaluation of forests and agricultural systems as a complement to economic analysis (Bastianoni et al., 2001; Odum, 2004; Cohen et al., 2006; Cavalett and Ortega, 2009; Li et al., 2011; Zhang et al., 2011; Lu et al., 2002; 2006; 2009a, b; 2011b; 2015b; 2017a,b; Cheng et al., 2017). In addition to their use in systems analysis, emergy methods were also specifically applied for evaluating the water and soil conservation functions of GFGP, i.e., using bamboo to replace crops in this study, as a reference for ecological compensation strategy-making.

All annual emergy inputs to and outputs from the corn-sweet potato farm system and the three bamboo plantations for both 3 and 8 year-old plantings were evaluated on the basis of the annual flows of 1 ha. The amortization period for the initial inputs of emergy to the bamboo plantations *i.e.*, seedlings and labor for planting, was assumed to be 75 years, considering that all these plantations can be harvested 3 to 8 years after planting with a period of active use of about 75 years, which is the period without the need for replanting (Bonilla et al., 2010; Feliserto et al., 2017). All emergy inputs were classified into local renewable resources (R), *e.g.*, sun, wind and rain; local potentially renewable resource that is being used in a nonrenewable manner ($N_0$) *i.e.*, topsoil loss; purchased resources (F), like seedlings, manure, chemical fertilizer, chemical pesticides and petroleum products (Fig.2.). In order to avoid double-counting of the local renewable resource (R), only the maximum input was taken into account (Odum, 1996). All inputs to the farmland or bamboo plantation systems, *e.g.*, rain, sunlight, labor, fertilizer, were converted to emergy using the appropriate unit emergy value (UEV) based on the 12E+24 seJ/yr planetary baseline (Brown et al., 2016). The emergy/money ratio of China in 2010 was deduced to be 5.51E+11sej/yuan based on the emergy/money ratio in 2005 (9.42E+11sej/yuan) found by Yang et al., (2010) by employing the relative GDP deflator for China from 2005 to 2010 (1.71, NBSC, 2011), considering a near linear correlation between real GDP and total national emergy consumption was found by Campbell et al., (2014). The soil and water erosion control of the three bamboo plantations was specifically quantified based on hydrological monitoring results. Taking the soil erosion and surface runoff from the cropland as a control, the relative water conservation and soil erosion control benefits of the three plantations in the first 3 years were quantified with application of the linear interpolation method. A suite of widely used emergy indices was calculated, i.e., Empower Density (EPD), Emergy Self-Sufficiency Ratio (ESR), Environmental Loading Ratio (ELR), Emergy Yield Ratio (EYR), Emergy Exchange Ratio (EER), Emergy Sustainability Index (ESI), Emergy Index for Sustainable Development (EISD), and Unit Emergy Value (UEV) (Table 2, Odum, 1996; Brown and Ulgiati, 1996; Lu et al., 2002, 2011).

Considering that soil erosion control is the main reason for the conversion, while economic yield from land is the fundamental concern of local farmers, a new index was formulated to measure the viability of the conversion, i.e. the soil intensity ratio (SIR) defined as the ratio of the emergy yield from the system to the soil erosion in emergy units ($Y/N_0$ in this study). Thus, SIR is a vector.

### 2.4. Economic analysis

It takes less than a year to get an economic return on the investment made in corn-sweet potato cropland, but 3 years to start getting economic returns from the BR and PA plantations, and 8 years from the PP plantations. Detailed economic inputs to and outputs from the plantations 3 and 8 years after conversion were investigated, and analyzed to explore the dynamic economic trends of the three bamboo plantations compared with those of the corn-sweet potato cropland. By considering the marginal cost and benefit of alternatives, many economic analysis methods have been widely used for dynamic cost and benefit accounting with the applying of a specific interest rate, such as the net present value method, the annual cost method, and the internal rate of return method (Esen et al., 2006; 2007; Esen and Yuksel, 2013). However, the interest rate is not a constant coefficient but a variable that changes with time, region and even lending institution. To account for the effects of deflation on the economic comparison and to make the economic analysis comparable with emergy synthesis, all economic benefits were converted to Chinese Yuan in 2010, by multiplying by the relative GDP deflators in China (NBSC, 2011).

From 2005 to 2010, the linear interpolation method was applied to deduce the economic characteristics of the plantations between ages 3 and 8 years’ old. Then, the economic characteristics of the bamboo plantations with and without accounting for the ecological compensation given to local farmers by the government were compared with that of the cropland. The economic benefits of the plantations on water conservation and in controlling soil erosion were quantified in emergy terms as a reference for the ecological compensation. We conclude with a brief discussion of ways to optimize the ecological compensation policy to further improve the GFGR program and to build the interest of local farmers in this program.

## 3. Results

### 3.1. Emergy evaluation

Detailed emergy analysis tables of the three bamboo plantations at 3 and 8 years’ old and of the farmland crop system are given in the Appendix in Tables A, B, C and D. All inputs to these systems were converted to solar emergy by multiplying the raw units by the relevant UEVs based on 12E+24seJ/yr planetary baseline, and then were converted to an Em-money value in EMyuan units through division by the emergy/money ratio of China in 2010. The market value of all inputs to and outputs from the systems under study were also given in these tables.

**3.1.1. Structure of emergy inputs—**Nature contributed more emergy than economic investment to both the bamboo plantations and the farmland crop systems, but with different shares of local renewable (R) and local potentially renewable resource that is being used in a nonrenewable manner ($N_0$) resources. Considering the local renewable resources, evapotranspiration made the largest R contribution to the 3 bamboo plantations, most of the time, while topsoil erosion was the largest input of $N_0$ to CP and to the 3-year-old PP. The $N_0$ input to CP (9.14E+15sej/ha/yr) was 3.18 to 92.79 times that to the 3 bamboo systems, which ranged from a maximum for the 3-year-old PP systems (2.87E+15 sej/ha/yr) to a minimum for the 8-year-old BR system (9.85E+13 sej/ha/yr). Simultaneously, the purchased inputs for CP (4.68E+15sej/ha/yr) were 10.15 to 238.51 times that of the 3 bamboo systems, which ranged from the largest for the 8-year-old PP system (4.61E+14 sej/ha/yr) to the least for the 3-year-old PP system (1.96E+13sej/ha/yr). Finally, the empower density of CP was 3.58 to 11.75 times that of the three bamboo plantations at 3 to 8 years' old (Fig.3.).

Due to the relatively lower annual precipitation in 2010, and the functional development in erosion control of the plantations, both the renewable and nonrenewable local resource inputs to the three 8-year-old bamboo plantations were lower than the same inputs to the 3-year-old plantations, which was also true of their total empower, although both the renewable and nonrenewable purchased inputs showed a reverse trend with more inputs required for the older systems.

**3.1.2. Emergy based soil and water erosion control—**Compared with CP, all three bamboo plantations showed better soil erosion control (Fig.4.). After a period of rapid increase during the first 3 years after planting, the benefits gained from soil erosion control slowed down markedly in all three bamboo plantations. The rate of erosion control benefits leveled from year 3 to 4 in BR and PA and then increased slowly in these systems from years 4 to 8. Benefits increased more gradually in PP, but eventually attained a similar level with BR and PA at 8 years' old.

Compared with CP, all three bamboo plantations had better water conservation, but the emergy value of water conservation was 2 orders of magnitude lower than the effects on soil erosion control. Similar to the trend seen in soil erosion control, the water conservation function of the three bamboo plantations quickly increased in the first 3 years after conversion, then the rate of increase slowed down, but still kept increasing at a speed of over 5% per annum (Fig.5.).

Compared with CP, the combined water conservation and soil erosion control function of all three bamboo plantations showed a similar increasing trend with the soil erosion control function, i.e. it quickly increased in the first 3 years, and then the speed of increase slowed down (Fig.6.). In the first 8 years, BR was the best for water conservation and soil erosion control, followed by PA and then PP. After 3 years, the water conservation and soil erosion control function of BR and PA was almost constant, while that of PP kept increasing at over 6% per year. Following this trend, PP will exceed PA and BR to be the best mode for water conservation and soil erosion control sometime after the plantations are 8 years' old.

**3.1.3. Emergy Self-Sufficiency Ratio (ESR) and Environmental Loading Raito (ELR)—**Without other economic input except the seedlings and the labor for planting and harvesting, all three bamboo plantations had their ESRs higher than 0.75 at both 3 and 8 years' old, while that of CP was only 0.69. Due to the addition inputs for harvesting, the ESRs of all three 8-year-old bamboo plantations were lower than at 3 years' old, especially that of PP which was only 75% of its value at 3 years' old.

All three bamboo plantations had their ELR lower than 2.15, which was less than 20% that that of CP (10.51). Although the labor input increased with the increased productivity of bamboo culms and shoots from 3 to 8 years' old, this increase in emergy inputs was balanced by a decrease in the nonrenewable local resources used (i.e. soil erosion). Finally, the ELRs of the three bamboo plantations at 8 years' old were 0.44 to 0.87 times that of their values at 3 years' old (Table 3).

**3.1.4. Emergy Yield Raito (EYR) and Emergy Exchange Ratio (EER)—**Without much input purchased from the economy, the EYRs of all three bamboo plantations at both 3 and 8 years' old were higher than 4, while that of CP was only 3.23 (Table 3). On the other hand, with the increasing productivity of bamboo shoots and culms in the older stands, more and more labor was used for harvesting. Consequently, the EYRs of all 8-year-old bamboo plantations were less than half of that when they were 3 years' old. In the extreme, the EYR of PP at 8 years' old was only 2% that of its value as a 3-year-old parcel.

All the systems under study benefited from trading their products on the market (EER>1), and all bamboo plots had EERs higher than that of CP (1.23), except for 3-year-old PP which had no economic output until it was 8 years' old. All three bamboo plantations had EERs at 3 years' old that were less than when they were 8 years' old. Due to the higher EER for bamboo shoots, the EERs of PA and PP were higher than that of BR for the same age stands.

**3.1.5. Emergy Sustainability Index (ESI) and Emergy Index of Sustainable Development (EISD)—**With relatively high EYRs (4.06-215.66) and low ELR (0.33-2.15), all three bamboo plantations had relatively high ESIs which ranged from 14.07 to 325.71 times that of CP (0.31). The ESIs of all 8-year-old plantations were lower than their values at 3 years' old, because of the greater input of labor required for harvest of the bamboo culms and/or shoots. At three years old, PP was the most sustainable alternative among the three bamboo plantations, followed by PA and BR. However, with the start of the harvesting of bamboo culms and shoots at 8 years' old, the ESI of PP (4.33) became the lowest among the three bamboo plantations, and the order of sustainability among the three bamboo plantations was reversed with BR becoming the most sustainable (Table 3).

After considering the superior position of the farmer in trading bamboo products, especially bamboo shoots, the three bamboo plantations had superior ecological economic characteristics promoting sustainable development, as shown by the fact that their EISDs ranged from 80.35 to 265.80 times that of CP. At 3 years' old, PA was the best system in terms of sustainable development considering economic effects, followed by PP and BR. However, at 8 years' old BR turned out to be the best alternative followed by PA and PP.

**3.1.6. Soil Intensity Ratio (SIR) and Unit Emergy Value (UEV)—**The soil intensity ratio quantifies the environmental impact of systems and processes on soil erosion. A higher SIR means more serious soil erosion to gain a unit of output. Most of the bamboo plantations had a SIR that was less than that of CP, except for 3-year-old PP (Table 3). For the three bamboo plantations, the SIRs at 8 years' old were all less than that at 3 years' old. BR had the least environmental impact due to soil erosion at both 3 and 8 years' old, followed by PA and PP.

For the same products a lower UEV means a higher production efficiency. For culm production, all bamboo plantations at 8 years' old were more efficient than those at 3 years' old (Table 3). BR was the most efficient alternative for culm production among the three plantations at both 3 and 8 years' old. At 8 years after conversion, PP started to have an output of culms and shoots, with its production efficiency between BR and PA for culms of the same age, and lower than PA for shoots at the same age.

## 3.2. Economic analysis

**3.2.1. Economic output/input ratio—**With only seedlings and labor as inputs required for planting and harvest, all three bamboo plantations had their O/I ratios higher than that of CP, i.e., at 3 years after planting for BR and PA, and 8 years after planting for PP (Fig.7.).

Although the ecological compensation was constant for 8 years (3450 yuan/ha/yr from 2003 to 2010), after considering GDP deflation, its purchasing power decreased from 7912.7 yuan/ha/yr in 2003 to 3450 yuan/ha/yr in 2010, based on the buying power of RMB in 2010. Consequently, after taking into consideration the ecological compensation as an extra economic benefit given to farmers, the $O_{EC}$/I of all three bamboo plantations progressively decreased, but was higher than that of CP in the first 8 years after conversion, especially in the first 2 to 7 years without labor input for harvest (Fig.8.).

Taking the emergy-based water and soil conversion value as a replacement for the applied ecological compensation, the $O_{EMC}$/I of all three bamboo plantations was higher than that of CP. Although the emergy-based water and soil conservation value kept increasing in all three bamboo plantations in the first 8 years after conversion, the $O_{EMC}$/I decreased due to the increased labor inputs for harvesting 3 and 8 years after conversion (Fig.9.). In the $8^{th}$ year after conversion, PA had the highest $O_{EMC}$/I (10.78), which was 6.18 times that of CP (1.74), followed by BR (7.73) and PP (3.66).

**3.2.2. Net economic benefit (NEB)—**Although the O/I ratio is a key economic characteristic, local farmers are much more concerned with the net economic benefit they can get from a unit area due to the limited availability of reclaimable land.

The NEB of BR remained lower than that of CP during the entire study period, while that of PA and PP rose from 0 to be higher than that of CP from the start of harvesting after 3 or 8 years for PA and PP, respectively (Fig.10.). On average, during the first 8 years after conversion, the NEBs of the three bamboo plantations were 928.01~12611.05 yuan/ha/yr lower than that of CP (14635.83 yuan/ha/yr).

The application of ecological compensation reduced the difference between CP and the bamboo plantations before harvest, but it did not change their relative negative economic benefit positions (Fig.11.). On average over the first 8 years after conversion, only PA had a Net Economic Benefit with ecological compensation ($NEB_{EC}$, 18896.10 yuan/ha/yr) that was higher than that of CP (14635.83yuan/ha/yr), while that of BR and PP were still respectively 3922.03 and 7422.77 yuan/ha/yr lower than that of CP.

Emergy-based ecological compensation gave all three bamboo plantations a positive net economic benefit, from the start of harvesting (Fig.12.). On average during the first 8 years after conversion, only PP had its $NEB_{EMC}$ lower than that of CP, while BR and PA had their $NEB_{EMC}$, respectively, 4859.89 and 12456.28yuan/ha/yr higher than that of CP.

## 4. Discussion

In recent years, the area of bamboo forest has increased rapidly in China, but also in other tropical and subtropical regions in Asia, Africa and South America (Felisberto et al., 2017). For example, bamboo plantations have been developed quickly in Brazil to grow bamboo culms as a substitution for traditional wood, with *Dendrocalamus gianteus* as the most widely used species. Growing *Dendrocalamus giganteus requires* a relatively high economic input (5.62E+15sej/ha/yr), as a result the empower of the *Dendrocalamus giganteus* plantation (abbreviated 'DG') was high ranging up to 7.66E+15sej/ha/yr (Bonilla et al., 2010). This is 3.12 to 4.60 times that of the three bamboo plantations in their harvest periods examined in this study. Consequently, the specific emergy of the culm of *Dendrocalamus gianteus* (3.48E+08sej/g) was 1.20 to 5.02 times that of the culms produced by the three bamboo plantations in this study. The above comparison quantitatively explored both the relatively lower environmental impact and the relatively higher productivity of the three bamboo plantations in this study compared to those in Brazil.

The measurements in this study disclosed that the conversion of cropland on hillsides to any of the three bamboo plantations examined here had positive effects on water conservation and soil erosion control, especially on soil erosion control. Planting bamboo on hillsides is even better in controlling erosion than some forest plantations restored on hillsides in Southeast China in the first 8 years after planting (Lu et al., 2017). Due to the economic inputs required for harvesting, the environmental loading ratios (ELRs) of the three bamboo plantations were higher than those of some forest plantations (Lu et al, 2009; Li et al., 2013; 2015), and similar to that of an agro-forest restoration system in lower subtropical China (Lu et al., 2006).

On average during the first 8 years after conversion, all three bamboo plantations produced less net economic benefit compared with cropland most of the time. These results also confirmed the study results of Ly et al. (2012), which showed that a shift in land use from annual crops to bamboo in northern Vietnam provided an annual net gain in soil organic carbon, but that conversion to bamboo was constrained by income insecurity in the early stages of plantation development, i.e., before bamboo grows large enough for harvesting, because it had a low economic return-per-unit area compared with annual cash crops like cassava, rice and maize. Bamboo is a planting system that produces relatively few marketable outputs, thus the EER and economic viability of the three bamboo plantations examined were lower than that of many agro-forest systems planted on hillsides in South China (Lu et al, 2006; Cheng et al., 2017).

To fill this gap and to make the GFGP successful, the Chinese government launched a suite of policies defining ecological compensation, which was finally set as 3450 yuan/ha/yr from 2003 to 2010 to be paid during the first 8 years after land conversion (Kong, 2007; Yu, 2014). However, even after counting in the ecological compensation, the net economic benefits of the three bamboo plantations were still lower than that of CP at most times during the study period. Only PA had a higher $NEB_{EC}$ than CP in the first 8 years after conversion. Furthermore, 8 years after conversion the $NEB_{EC}$ of BR was still lower than that of CP. These difficulties showed that a better ecological compensation strategy is needed to improve the viability of the bamboo plantations, both during and after the first 8 years since conversion. How to secure the conservation benefits of the GFGP planting modes in the post GFGP period, when the GFGP modes have less economic viability is of broad concern to both governments and researchers. An ideal way to accomplish this is to set-up ecological compensation strategies based on objective evaluations of the ecosystem services gained by the GFGP planting modes (Guo et al., 2014; Liu, 2014; SFAPRC, 2015; Wu, 2017). However, how to quantify the value of ecosystem services objectively, and how to include them in the current value system is still a problem (Costanza et al., 2017).

The emergy-based value of ecosystem services provided by water conservation and soil erosion control were quantified as a donor side reference for ecological compensation. The results showed that all three bamboo plantations had a higher $NEB_{EMC}$ than CP after the start of harvesting. Taking the first 8 years as a whole, only PP had its annual $NEB_{EMC}$ 945.97yuan/ha/yr lower than that of CP. Clearly, emergy-based ecosystem services valuation is an objective reference for ecological compensation, but it needs complicated ecological and economic measurements, investigation and analysis to define such compensation (Campbell and Tilley, 2014a;b; Lu et al., 2017). In the case under study, how to improve the economic viability of the bamboo plantations before their harvesting period is a key problem that needs to be solved.

Developing integrated agro-forest modes has been reported to be a good option for improving the economic viability of bamboo plantations in many places, e.g. the *Phyllostachys edulis- Dictyophora echinovolvata, and Phyllostachys pubscense-Tarastigma hemsleyamnum* modes in Zhejiang Province (Wu et al., 2016; Wang et al., 2016), the *Phyllostachys pubscense- Polygonatum cyrtonema* and *Phyllostachys pubscense-Anoectochilus roxburghii* modes in Fujian Province (Zhang, 2012; Li, 2016), but no long term studies and integrated ecological economic evaluations of such innovations that incorporates the production of medicinal herbs and edible fungus within bamboo cultivation has been funded or carried out to date. All these restoration modes can be found in Chang-ning county, although no research publications were found in the literature describing them.

The area covered by *Dictyophora echinovolvata* has quickly expanded in Chang-ning county, reaching 1467 ha in 2016. The Chinese government designated Chang-ning county as the primary agricultural conservation area for *Dictyophora echinovolvata* in 2016. Measurement and analysis of these agricultural development modes using bamboo in the GFGR program is needed to optimize the mix of land use for more sustainable regional development. In addition, since bamboo forests are rapidly expanding not only in China but also in other tropical areas, the structural and functional development of succession mechanisms for bamboo forests, and their consequences for global change have been gaining world-wide attention (Jiang, 2007; Yang, 2012). To fill this gap, a long-term bamboo forest ecology research station was established in Chang-ning county in 2016 by the State Forestry Administration of China.

## 5. Conclusion

1. Using bamboo plantations to replace sloping cropland can effectively decrease topsoil erosion which is the main target of the GFGP.
2. The erosion control function of the three bamboo plantations kept increasing during the first 8 years after conversion.
3. All three bamboo plantations were much more sustainable than common conventional crops grown on sloping land on both the short and long-term scales of temporal analysis, having relatively low ELRs, but higher ESRs, EYRs, and EERs ratios.
4. Due to lower economic density and a relatively long economic return cycle for investments, all three bamboo plantations had NEBs less than that of CP, during the first 8 years after conversion. Even with the government mandated ecological compensation applied, the annual $NEB_{EC}$ of BR and PP were still 3922.03 and 7422.77yuan/ha/yr lower than the NEB (14635.83 yuan/ha/yr) of CP.
5. Emergy-based evaluation of ecological benefits, such as water conservation and soil erosion control provides an objective reference for assigning the benefits mandated by ecological compensation, but even if followed it cannot wholly solve the economic viability problem for all of the bamboo plantations. Inter-planting annual crops with economic value such as, herbs or a fungus, such as *Dictyophora echinovolvata*, under the canopy of bamboo plantations, especially in young bamboo plantations, might be a direction for optimization of economic viability during the first years after conversion.

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**Fig.1.**
The geographical context and location of Chang-ning County

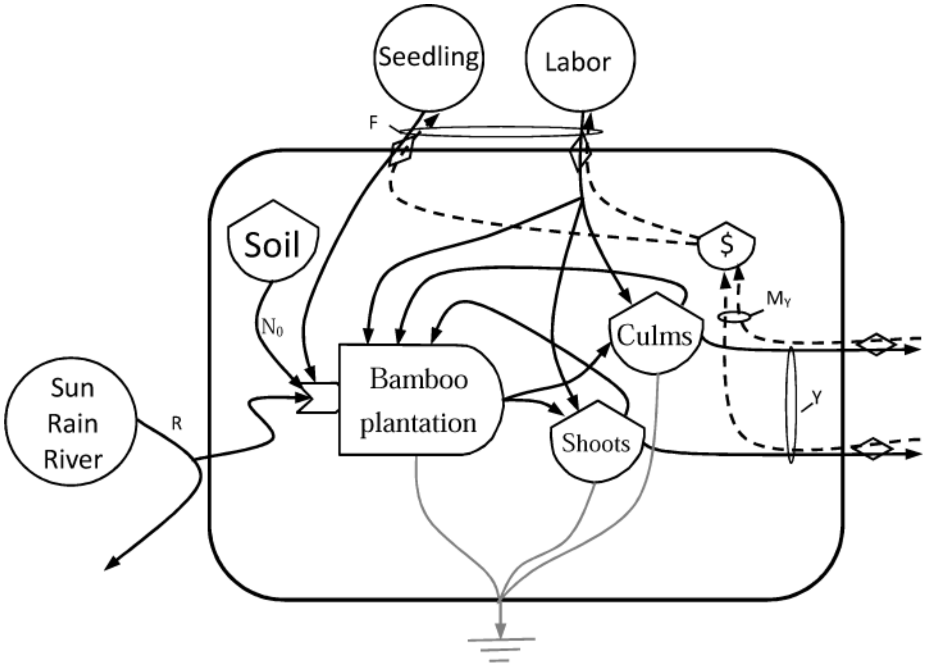

**Fig.2. Energy Systems Language diagram of the bamboo plantations**

R=local renewable resources, $N_0$= local potentially renewable resource that is being used in a nonrenewable manner, i.e. being used quickly than its replacement; F=purchased resources; $M_Y$= emergy buying power of the money received by trading the yield in the market.

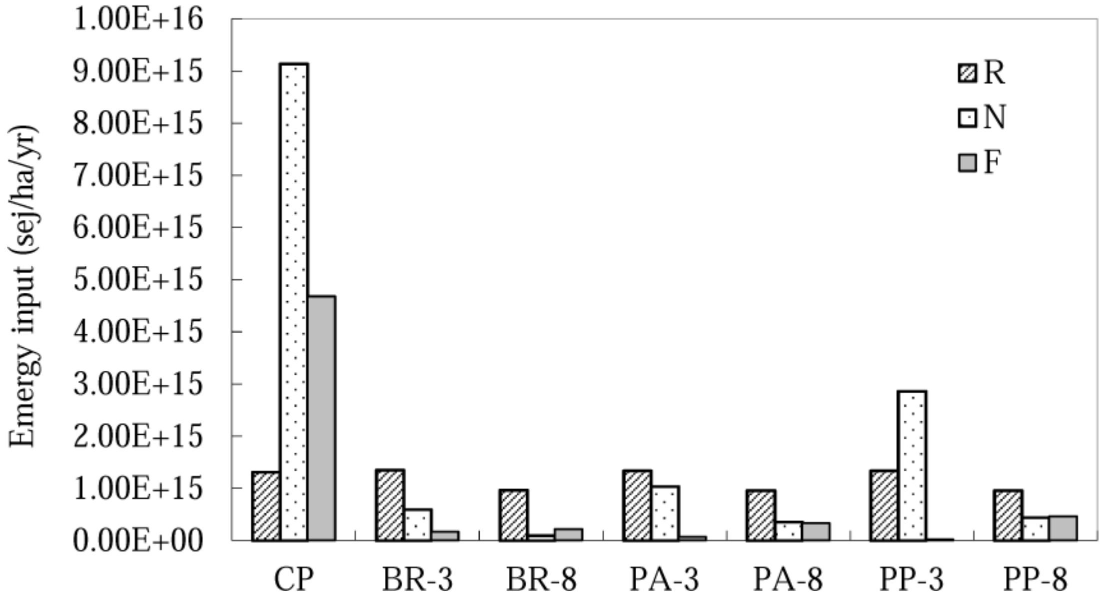

**Fig.3. Aggregate structure of the emergy inputs to the 4 systems**

(CP: corn-sweet potato system; BR-3: *Bambusa rigida* plantation at 3 years old, and the same for BR-8, PA-3, PA-8, PP-3 and PP-8)

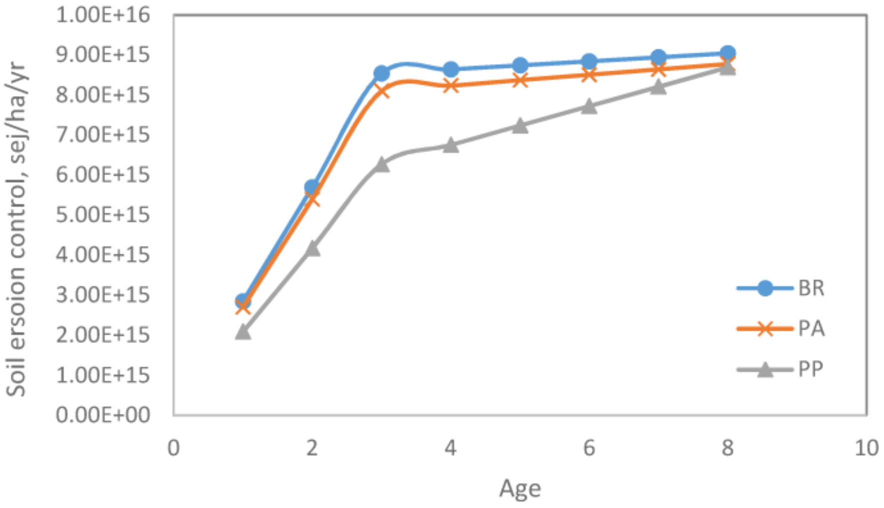

**Fig.4.**

Relative soil erosion control of the three bamboo plantations

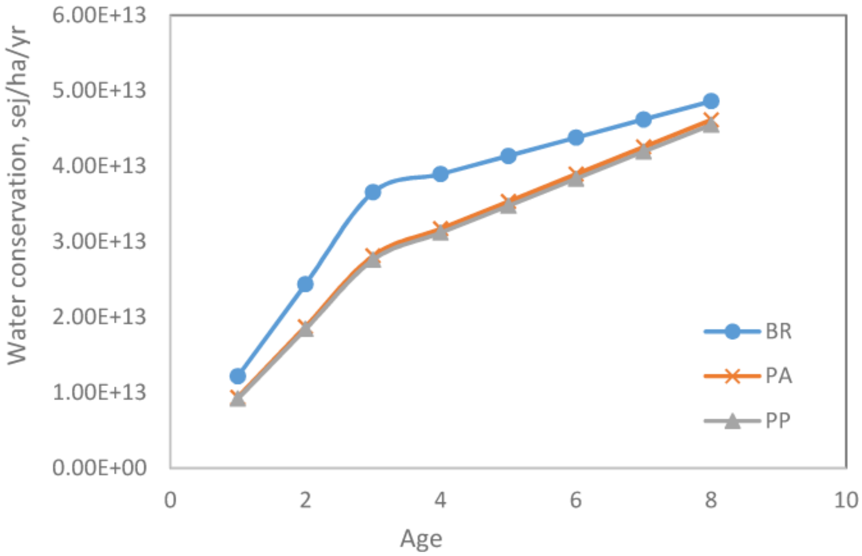

**Fig.5.**

Relative water conservation of the three bamboo plantations

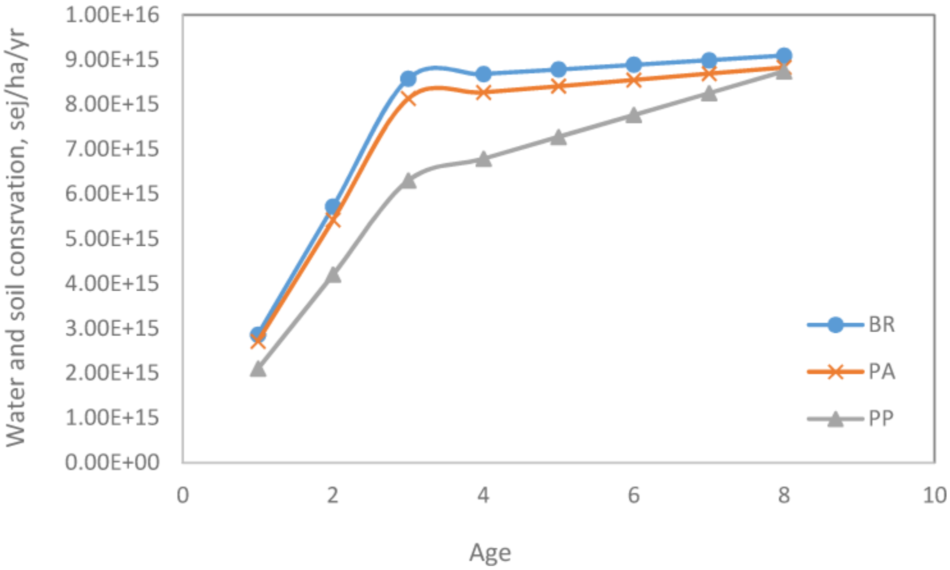

**Fig.6.**

Relative water and soil conservation of the three bamboo plantations

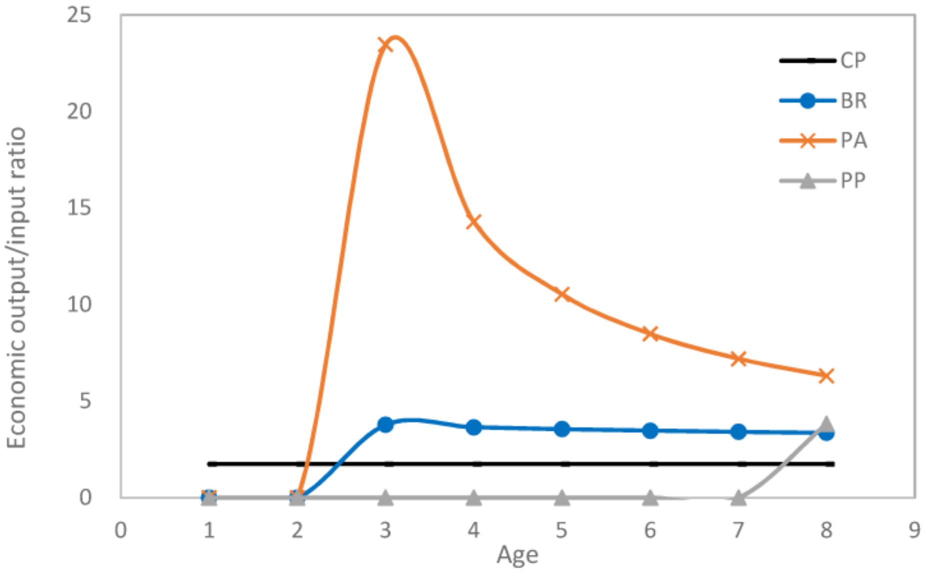

**Fig.7.**

Economic output/input ratios of the cropland and the three bamboo plantations after conversion

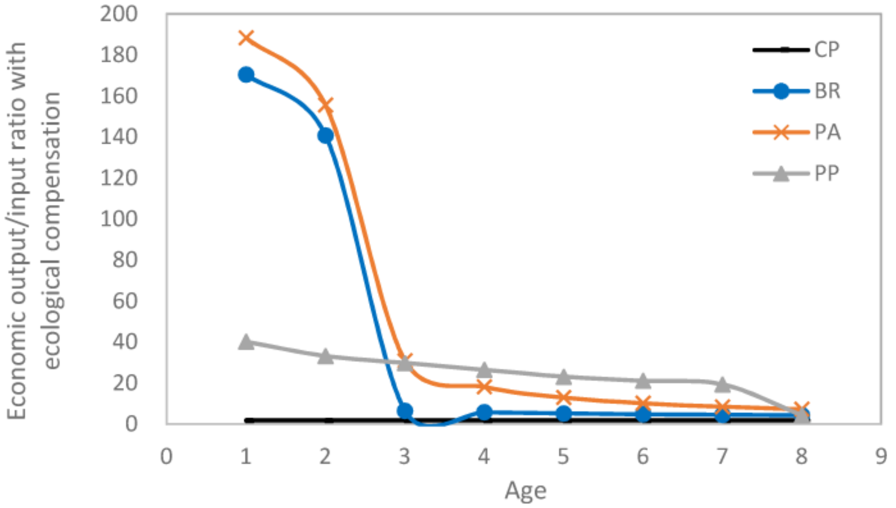

**Fig.8.**

Economic output/input ratios of the cropland and the three bamboo plantations with ecological compensation

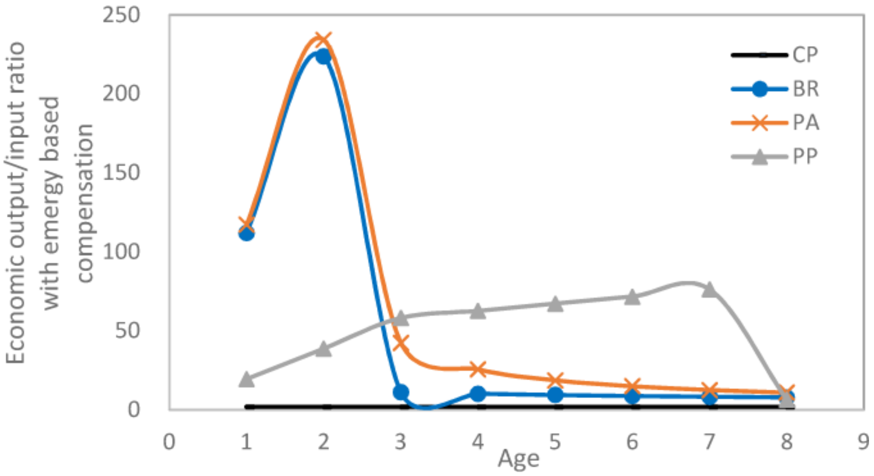

**Fig.9.**

Economic output/input ratios of the cropland and the three bamboo plantations with emergy-based compensation

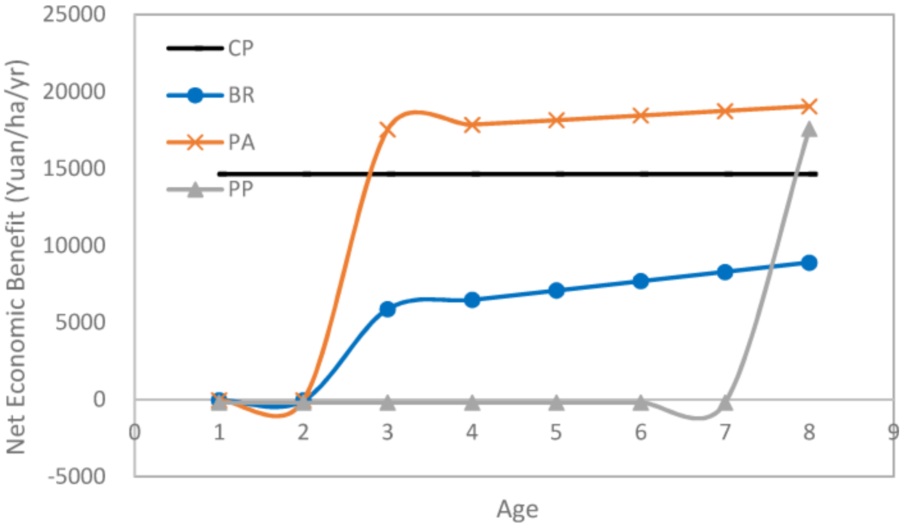

**Fig.10.**

Net economic benefits of the cropland and the three bamboo plantations

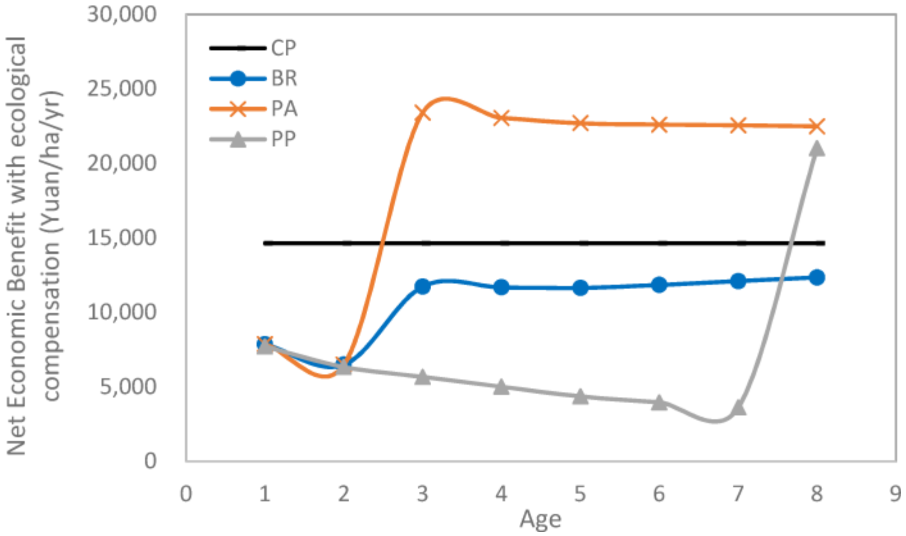

**Fig.11.**

Net economic benefit of the cropland and the three bamboo plantations with ecological compensation

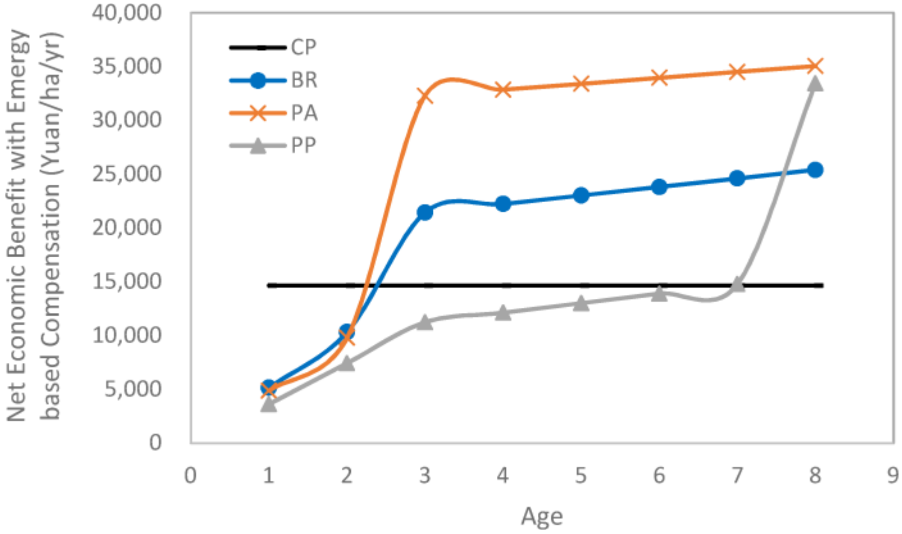

**Fig.12.**

Net economic benefit of the cropland and the three bamboo plantations with emergy-based compensation

## Table 1

Growth and harvest parameters for the four systems

| Items | CP | BR | PA | PP |
|---|---|---|---|---|
| Slope degree | 18 | 20 | 25 | 30 |
| Altitude(m) | 345 | 375 | 355 | 355 |
| Time scale | – | 3 and 8 years | 3 and 8 years | 3 and 8 years |
| Time for highly dense canopy | – | 3–4years | 3–4 years | 8–9 years |
| Management | Planted sweet potato and corn | Cut culms each year | Harvest bamboo shoots and cut culms every year | Dig bamboo shoots in winter and cut culms every other year |
| Soil type | Yellow earth | Yellow earth | Yellow earth | Yellow earth |
| Main applications in market | Sweet potato was used to produce starch; corn was for food | Raw material for paper production | Produces edible bamboo in summer, and culms as raw material for paper or farm tool production | Produces edible bamboo shoots in winter, and culms as raw material for architecture, furniture and decorations etc. |

## Table 2

Emergy indices employed in this study

| Index | Formulation | Reference |
|---|---|---|
| Empower Density (EPD) | U/area | Odum (1996) |
| Specific emergy | Y/mass | Odum (1996) |
| Emergy Self-Sufficiency Ratio(ESR) | $(R+N_0)/U$ | Odum (1996) |
| Environmental Loading Ratio (ELR) | $(F+ N_0)/R$ | Brown and Ulgiati (1996) |
| Emergy Yield Ratio (EYR) | Y/F | Odum (1996) |
| Emergy Sustainability Index (ESI) | EYR/ELR | Brown and Ulgiati (1996) |
| Emergy Exchange Ratio (EER) | $M_Y/Y$ | Odum (1996) |
| Emergy Index of Sustainable Development (EISD) | EYR*EER/ELR | Lu et al., 2002 |
| Soil Intensity Ratio (SIR) | $N_0/Y$ | This study |

## Table 3

Emergy indices of the crop system and the bamboo plantation at 3 and 8 years’ old

| **Index** | **CP** | **BR** | | **PA** | | **PP** | |
|---|---|---|---|---|---|---|---|
| | **—** | **3 years’ old** | **8 years’ old** | **3 years’ old** | **8 years’ old** | **3 years’ old** | **8 years’ old** |
| EPD (sej/ha/yr) | (1.51E+16)±(1.79E+14) | (2.12E+15)±(2.30E+13) | (1.29E+15)±(9.98E+12) | (2.46E+15)±(5.29E+12) | (1.67E+15)±(1.78E+13) | 4.23E+15 | (1.87E+15)±(3.84E+12) |
| UEV (sej/g) | (2.06E+8)±(4.71E+7) (sweet potato) | — (shoot) | — (shoot) | (2.86E+8)±(2.84E+7) (shoot) | (1.93E+8)±(1.15E+7) (shoot) | — (shoot) | (2.35E+8)±(9.41E+6) (shoot) |
| | (5.20E+8)±(1.18E+8) (corn) | (1.62E+8)±(1.02E+7) (culm) | (6.93E+7)±(3.30E+6) (culm) | (2.87E+8)±(2.82E+7) (culm) | (1.29E+8)±(1.28E+7) (culm) | (1.00E+9)±(2.85E+8) (culm) | (8.22E+7)±(1.25E+6) (culm) |
| ESR | 0.69±0.01 | 0.92±0.01 | 0.83±0.01 | 0.97±0.00 | 0.80±0.01 | 1.00±0.00 | 0.75±0.00 |
| EYR | 3.23±0.09 | 12.76±1.62 | 5.86±0.23 | 33.24±2.29 | 4.97±0.21 | 215.56±0.00 | 4.06±0.03 |
| ELR | 3.04±0.51 | 0.57±0.02 | 0.33±0.01 | 0.83±0.00 | 0.72±0.02 | 2.15±0.00 | 0.94±0.00 |
| ESI | 1.08±0.16 | 22.47±3.53 | 17.85±1.27 | 40.13±2.95 | 6.88±0.46 | 100.21±0.00 | 4.33±0.05 |
| EER | 1.23±0.04 | 1.97±0.12 | 5.42±0.25 | 3.93±0.30 | 7.48±0.56 | 1.00±0.00 | 7.00±0.19 |
| EISD | 1.32±0.17 | 44.11±4.59 | 96.51±2.49 | 157.34±5.78 | 51.33±1.07 | 100.21±0.00 | 30.29±0.71 |
| SIR | 0.60±0.01 | 0.28±0.00 | 0.08±0.00 | 0.42±0.00 | 0.22±0.00 | 0.68±0.00 | 0.17±0.12 |