Journal of Zhejiang University-SCIENCE B (Biomedicine & Biotechnology)
ISSN 1673-1581 (Print); ISSN 1862-1783 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Emergy assessment of three home courtyard agriculture production systems in Tibet Autonomous Region, China*

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Received June 24, 2015; Revision accepted Nov. 9, 2015; Crosschecked July 13, 2016

Abstract: Home courtyard agriculture is an important model of agricultural production on the Tibetan plateau. Because of the sensitive and fragile plateau environment, it needs to have optimal performance characteristics, including high sustainability, low environmental pressure, and high economic benefit. Emergy analysis is a promising tool for evaluation of the environmental-economic performance of these production systems. In this study, emergy analysis was used to evaluate three courtyard agricultural production models: Raising Geese in Corn Fields (RGICF), Conventional Corn Planting (CCP), and Pea-Wheat Rotation (PWR). The results showed that the RGICF model produced greater economic benefits, and had higher sustainability, lower environmental pressure, and higher product safety than the CCP and PWR models. The emergy yield ratio (EYR) and emergy self-support ratio (ESR) of RGICF were 0.66 and 0.11, respectively, lower than those of the CCP production model, and 0.99 and 0.08, respectively, lower than those of the PWR production model. The impact of RGICF (1.45) on the environment was lower than that of CCP (2.26) and PWR (2.46). The emergy sustainable indices (ESIs) of RGICF were 1.07 and 1.02 times higher than those of CCP and PWR, respectively. With regard to the emergy index of product safety (EIPS), RGICF had a higher safety index than those of CCP and PWR. Overall, our results suggest that the RGICF model is advantageous and provides higher environmental benefits than the CCP and PWR systems.

Key words: Home courtyard agriculture, Raising Geese in Corn Field, Conventional Corn Planting, Pea-Wheat Rotation, Emergy, Sustainability
http://dx.doi.org/10.1631/jzus.B1500154 **CLC number:** F062.2; S344.9

1 Introduction

The Tibet Autonomous Region covers approximately one-eighth of Chinese territory. Because of the harsh environmental conditions, only the regions of the Yalongzangpo River and its two tributaries, the Nyachu and Lhasa Rivers, provide suitable conditions for agricultural production (Paltridge *et al.*, 2011). Barley (*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.), pea (*Pisum sativum* L.), and rape (*Brassica campestris* L.) are the main cash crops. Farm size is generally less than 1 ha, and historically, crop yields have been low (4.5 t/ha for winter wheat and 4.3 t/ha for barley) and incomes in rural areas average <2 USD per day (Sinclair and Bai, 1997; Tashi *et al.*, 2002; TSY, 2007; Paltridge *et al.*, 2009). In recent years, agrochemicals have been used increasingly to improve crop yields and hence economic benefit. Input of chemical fertilizer reached 143 000 t in 2012, which was approximately 1.8 times that of 1993 (Wang, 2014). Input of pesticide reached 3141 t in

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* Project supported by the National Natural Science Foundation of China (No. 31201594), the Science and Technology Service Network Initiative of CAS (No. KFJ-EW-STS-073), and the Development Platform of Wild Characteristic Biological Resources in Tibet Autonomous Region, China

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2008, approximately 1.4 times that of 1993 (Wang, 2014). Although use of these agrochemicals may improve crop yield and economic benefit, their potential negative effects are of public concern. The plateau environment is sensitive and fragile, and intensive farming may cause irreversible damage such as soil erosion and the loss of species diversity and product quality (Feng *et al*., 2009; Tao *et al*., 2013).

Compared with intensive agriculture, traditional home courtyard agriculture has been reported to have more economic and ecological benefits, including the maintenance of higher species diversity (Fernandes and Nair, 1986; Norfolk *et al*., 2013), improved soil fertility (Munyanziza *et al*., 1997), water retention (Roose and Ndayizigiye, 1997), and food security (Fernandes and Nair, 1986; Jose and Shanmugaratnam, 1993). Traditional home courtyard agriculture has been developed in the Tibetan plateau over many years. Tibetan rural households have cultivated their courtyards for crops, and raised livestock such as yak, cattle, the Tibetan chicken, and the Tibetan pig. Animal manure is used for fertilizer. In addition, nitrogen input is increased via cultivation of legumes (mainly field peas) (TSY, 2007). However, the amount of food produced in courtyards does not meet the consumption needs of households, let alone create economic benefit for others (Liu *et al*., 2008). The use of chemical fertilizer and pesticides does create some surplus value, but long-term agriculture based on their use is not sustainable. For this reason, a new courtyard agriculture production model, which has a modest impact on the environment and yields high quality products securely and with economic benefits, should be explored.

Raising Geese in Corn Fields (RGICF) is a compound production model based on the principle of "Agro-pastoral Integration," which was proposed in 2011. In this model, waste resources such as weeds and the bottom leaves of crops from the tillage system are used to raise poultry (Guan *et al*., 2013a; 2013b). This method has been found to maintain species diversity and create high economic benefits (Sha *et al*., 2014; Zhang Y.Y. *et al*., 2014a). However, we do not have a comprehensive understanding of the performance of this agricultural production system, including its overall efficiency, input-output status, and resource-use efficiency. It is important to understand the internal operating mechanisms of production, as well as to assess the potential ecological and economic benefits.

Contributions to agricultural production include natural and economic inputs. However, the difficulty in assigning value to the natural contributions leads to a gap in the assessment of the value of natural resources and that of economic resources (Odum, 1988; 1996; 2007; Zeng *et al*., 2013). The Emergy Analysis methodology was proposed by Odum (1996). This method takes into consideration information, material, energy, and monetary flows from both natural and economic systems that were acquired directly or indirectly to create products and services, and all of these resources can be translated into the common unit, solar emjoule or sej (Odum, 1988; Lan *et al*., 2002). Emergy Analysis has been applied to different fields, and it has become a promising tool for evaluation of ecological-economic systems (Castellini *et al*., 2006; Zhang *et al*., 2007; Coppola *et al*., 2009; Vassallo *et al*., 2009). In addition, it has been used to assess agricultural production on different scales (Campbell, 2001; Chen *et al*., 2006; la Rosa *et al*., 2008; Pizzigallo *et al*., 2008; Xi and Qin, 2009; Lu *et al*., 2010).

The aim of this study was to determine whether RGICF should be popularized in Tibet Autonomous Region, China by using emergy analysis to evaluate comprehensively the energy input-output structure, environmental impact, systematic sustainability, product safety, and economic benefit of the RGICF production model compared with Conventional Corn Planting (CCP) and local conventional Pea-Wheat Rotation (PWR).

2 Materials and methods

2.1 Location and study site

The study was carried out in the village of Zhangmai, in the town of Bayi, (29°33′ N, 94°21′ E) in the valley downstream from the Niyang River. The topography is sloping fields 2980–3100 m above sea level. The climate is typical of Southeast Tibet, being warm and sub-humid, with an annual average temperature of 8.6 °C, an average annual daytime temperature of ≥10 °C for 159.2 d/year, an average annual accumulated temperature (≥10 °C) of 2225.7 °C, an average frost-free period of 177 d/year, average annual sunshine of 1988.6 h, and average sunshine percentage of 46%.

2.2 Study design and experimental methods

This experiment was conducted in household courtyards in 2012. Three courtyard production systems, RGICF, PWR, and CCP, were assembled in the experimental area. Each production model was set up in a split-split plot design with three blocks, and each sub-plot covered an area of 80 m^2. The corn rows were spaced 70 cm apart. A layer of plastic film was mulched and fertilizers were applied at planting (compound fertilizer, 240 kg/ha, which consisted of 33% nitrogen, 17% phosphorus, 17% potassium, and 20% organic matter). The RGICF sub-plots were enclosed by nylon nets 0.5 m high. No herbicide was applied and no weeds were removed manually. On July 10, we conducted rotational grazing of geese that were 30-d old in the RGICF sub-plots, providing them with sufficient water for the grazing period. The geese were captured and confined in the evening to prevent them from succumbing to natural enemies. They were given additional fodder (100 g/goose). In the CCP production model, chemical herbicide, which consisted of 90% atrazine and 10% mesotrione, was applied twice by backpack sprayer with fan nozzle to eradicate weeds, the first time after germination and then 50 d later. Irrigation was not conducted in either the RGICF or CCP model.

The PWR production model is the traditional cropping system used in Tibetan household courtyards. The pea rows were spaced 25 cm apart. Compound fertilizer (240 kg/ha, consisting of 33% nitrogen, 17% phosphorus, 17% potassium, and 20% organic matter) was applied at sowing. The growth phase is from late April to August when there is no farmland management. Winter wheat was sown on October 1, 2012, with 25-cm spacing between rows. The plots were irrigated twice during the wheat-growing period, first after the recovering stage (April 1, 2013), and then before the filling stage (June 15, 2013). The herbicide 2,4-D butylate was applied on April 1, 2013, for weed control, with the same application method as used for the CCP production model.

2.3 Emergy method

As in other agricultural systems, the three production systems are driven by natural resources and economic investments, many of which can be directly or indirectly derived from solar energy. Analysis of solar emergy (i.e., the available solar energy directly or indirectly required to make a product or service) (Yang and Chen, 2014) integrates the value of free natural resources, goods, services, and information into a common unit (sej), and proves a feasible tool to consider both economic profitability and environmental sustainability (Wang, 2014). The first step in standard emergy analysis is drawing an aggregated systems emergy diagram based on the energy circuit symbols introduced by Odum (1983; 1996). This diagram illustrates the boundaries of the systems, the main components and their interrelation, and material and energy flows. The aggregated systems diagrams for the different production systems are presented in Figs. 1–3.

The second step is establishing emergy tables. Inventories were compiled of the inputs and outputs of the three production systems during the growing seasons of 2012 and 2013. Inputs are categorized as renewable natural resources (R), non-renewable natural resources (N), purchased resources (F), and feedback energy (R_2). Renewable natural resources include sunlight and wind; an example of a non-renewable natural resource is top soil loss; purchased resources include machinery, labor, fuel, electricity, fertilizer, irrigation water, herbicide, seed, and baby geese. Feedback energy includes geese feces in the RGICF model and nitrogen fixation in the PWR model. Nitrogen fixation by peas was counted as 30 000 kg/ha (the fresh biomass of peas)×0.33% (the tested nitrogen content of the peas)×2/3 (the observed ratio for nitrogen fixation)=66 kg/ha (Mao, 1997). All inputs and outputs were converted to solar emergy by multiplying by the corresponding conversion factors (unit emergy value, UEV) that were obtained from previous studies and unified using the 15.20×10^{24} sej/year baseline. All other baselines were converted into 15.20×10^{24} sej/year through the corresponding coefficients such as 1.61 for 9.44×10^{24} sej/year, 1.64 for 9.26×10^{24} sej/year, and 0.96 for 15.38×10^{24} sej/year (Zhang X.H. *et al.*, 2014).

Based on the different renewability properties of the resource inputs, the renewability factors (RT) of each item have been considered in this paper in order to divide the inputs into their renewable and non-renewable proportions that are used for the calculation of the emergy-based indicators (Ulgiati *et al.*, 1994; Ortega *et al.*, 2005; Cavalett *et al.*, 2006; Hu *et al.*, 2011). The purchased inputs, F, were separated into the renewable proportion of purchased resources (F_R) and the non-renewable proportion of purchased resources (F_N).

The final step is to calculate emergy-based indices that can be used to assess various aspects of performance, such as resource use efficiency, environmental impact, and system sustainability. It is essential to introduce the following emergy-based indices:

(1) Emergy yield ratio (EYR) measures the ability of a productive process to exploit local resources that are fed back from outside the production model (Brown and Ulgiati, 1997): the higher the ratio, the higher the ability. EYR can be expressed as follows: EYR=$Y/(F_N+F_R)$, where Y is total yield emergy.

(2) Emergy self-support ratio (ESR) indicates the proportion of total emergy input from local natural resources (Odum, 1996): the higher the ratio, the higher the autarkic ability of the system. This ratio is expressed as follows: ESR=$(R+N)/U$, where U is the total emergy input of system.

(3) Environment loading ratio (ELR) is an indicator of the pressure of the productive process on the local environment, which was proposed by Brown and Ulgiati (1997): $(F+N)/R$. F represents material (M) and service (S), and therefore, ELR can be expressed as $(M+S+N)/R$. The renewability of purchased inputs was first considered by Ortega *et al.* (2005), who modified ELR by dividing F into F_R and F_N; in this way, both material and service can also be defined as renewable and non-renewable (M_R+M_N; S_R+S_N). Renewable material (M_R) and service (S_R) enhance the processing capacity, whereas non-renewable material (M_N) and service (S_N) cause environmental load. Therefore, ELR can be expressed as $(F_N+N)/(R+F_R)$ or $(M_N+S_N+N)/(R+M_R+S_R)$.

(4) Emergy sustainable index (ESI) measures the sustainability of the productive process: the higher the ESI, the more sustainable the production system (Brown and Ulgiati, 1997). The value can be expressed as follows: ESI=EYR/ELR.

(5) Feedback yield emergy (FYE) evaluates the self-organizing ability of the system: the higher the FYE, the higher the ability of the system to self-organize. This emergy is expressed as follows: FYE=$R_2/(F_N+F_R)$.

(6) Emergy index of product safety (EIPS) assesses the effect of chemical fertilizer and herbicide use on product security: the higher the EIPS, the higher the security of the products. EIPS=$1-C/(F_N+F_R)$, where C is the sum of herbicide and fertilizer emergy.

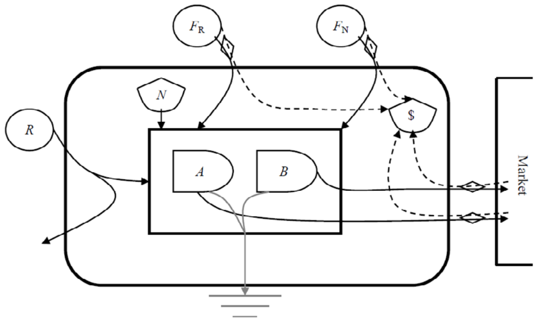

Fig. 1 Emergy flow diagram for the CCP production model

A: corn production in 2012; *B*: corn production in 2013; *R*: renewable natural resource input; *N*: non-renewable natural resource input; F_N: non-renewable purchased emergy input; F_R: renewable purchased emergy input

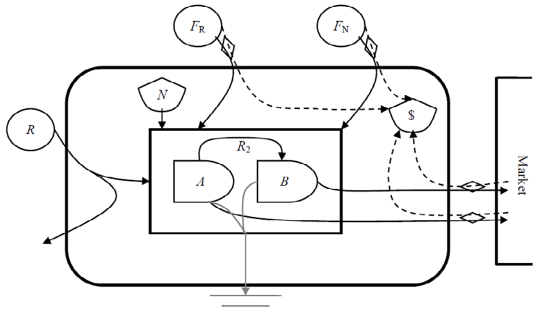

Fig. 2 Emergy flow diagram for the PWR production model

A: pea production in 2012; *B*: wheat production in 2013; *R*: renewable natural resource input; *N*: non-renewable natural resource input; F_N: non-renewable purchased emergy input; F_R: renewable purchased emergy input; R_2: feedback emergy in the system

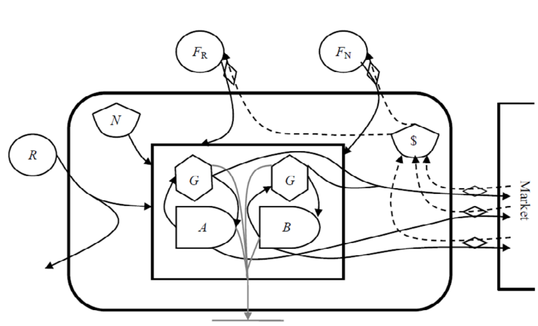

Fig. 3 Emergy flow diagram for the RGICF production model

A: corn production in 2012; *B*: corn production in 2013; *R*: renewable natural resource inputs; *N*: non-renewable natural resource input; F_N: non-renewable purchased emergy input; F_R: renewable purchased emergy inputs; *G*: geese raising

2.4 Economic analysis

The economic performances of RGICF and CCP were assessed using conventional economic analysis methods. The inputs and outputs were calculated using local market prices and the average exchange rate of Yuan to USD between 2012 and 2013 (6.25 Yuan to 1 USD).

3 Results

3.1 Emergy input and output analyses for the three production systems

The emergy input-output tables calculated for the three production systems (Tables 1–3) are also shown as aggregated diagrams in Figs. 1–3.

Table 1 Emergy evaluation of the RGICF production model

No.	Item	RT	Raw data	UEV[a]	Solar emergy (sej)
	Renewable natural resources (*R*)				
1	Sunlight (J)[b]	1.00	1.55×10^{12}	1.00	1.55×10^{12}
2	Wind, kinetic (J)[c]	1.00	1.04×10^{9}	2.35×10^{3}	2.44×10^{12}
3	Rain (J)[d]	1.00	4.20×10^{9}	2.93×10^{4}	1.23×10^{14}
	Total renewable natural resources				1.27×10^{14}
	Non-renewable resource (*N*)				
4	Net topsoil loss (J)[e]	0	1.35×10^{8}	1.19×10^{5}	1.60×10^{13}
	Total non-renewable resource				1.60×10^{13}
	Purchased resource (*F*)				
5	Water (J)	0	2.51×10^{7}	2.97×10^{4}	7.44×10^{11}
6	Fodder (g)	0.25	1.00×10^{5}	2.00×10^{9}	2.00×10^{14}
7	Machinery depreciation (USD)	0.05	30.20[f]	3.67×10^{12}	1.11×10^{14}
8	Fuel (J)	0.05	9.56×10^{7}	1.06×10^{5}	1.01×10^{13}
9	Film (g)	0.05	5.00×10^{3}	6.10×10^{8}	3.05×10^{12}
10	Compound (g)	0.05	6.40×10^{3}	4.90×10^{9}	3.14×10^{13}
11	Nylon net (g)	0.05	3.90×10^{2}	4.44×10^{9}	1.73×10^{12}
12	Heating device (USD)	0.05	6.44	3.67×10^{12}	2.36×10^{13}
13	Medicine (USD)	0.05	5.16	3.67×10^{12}	1.89×10^{13}
14	Land rent (USD)	0.05	68.60	3.67×10^{12}	2.52×10^{14}
15	Hydropower (J)	0.80	1.19×10^{9}	1.97×10^{5}	2.35×10^{14}
16	Labor (J)	0.60	9.05×10^{7}	2.79×10^{6}	2.52×10^{14}
17	Corn seeds (USD)	0.05	8.02	3.67×10^{12}	2.94×10^{13}
18	Baby geese (g)	0.20	2.00×10^{3}	1.45×10^{10}	2.90×10^{13}
	Total purchased emergy				1.20×10^{15}
	Total renewable purchased emergy (F_R)				4.20×10^{14}
	Total renewable purchased emergy (F_N)				7.79×10^{14}
	Feedback emergy in the system (R_2)				
19	Geese feces (g)		1.10×10^{4}	2.84×10^{9}	3.13×10^{13}
	Total feedback emergy in the system				3.13×10^{13}
	Total emergy input (*U*)				1.34×10^{15}
	Output (*Y*)				
20	Geese (g)		4.60×10^{4}	1.45×10^{10}	6.67×10^{14}
21	Straw (g)		5.60×10^{5}	6.59×10^{8}	3.69×10^{14}
22	Corn (g)		3.86×10^{5}	1.98×10^{9}	7.63×10^{14}
	Total output emergy				1.80×10^{15}

RT: renewability factors. [a] UEV references for respective row number: 1, 2, 3, and 4 refer to Zhang X.H. *et al.* (2014); 8, 15, and 16 refer to Campbell and Ohrt (2009); and 5, 6, 9, 10, and 11 refer to Lu *et al.* (2014) with the baseline of 9.26×10^{24} sej/year (UEVs adopted from that paper is multiplied by 1.64 for conversion to the new baseline of 15.20×10^{24} sej/year); 7, 12, 13, 14, and 17 refer to Liu *et al.* (2015) with the baseline of 9.44×10^{24} sej/year (UEVs adopted from that paper is multiplied by 1.61 for conversion to the new baseline of 15.20×10^{24} sej/year); 18, 19, 20, 21 and 22 refer to Castellini *et al.* (2006) with the baseline of 15.83×10^{24} sej/year (UEVs adopted from that paper is multiplied by 0.96 for conversion to the new baseline of 15.20×10^{24} sej/year). [b] Solar emergy=(average radiation)×(area)×(1−albedo)=(8.08×10^{9} J/(m^2·2-year))×(240 m^2)×(1−0.2)=1.55×10^{12} J/2-year. [c] Wind kinetic energy=(area)×(air density)×(drag coefficient)×(geostrophic wind)^3×(3.145×10^{7} s/year)=(240 m^2)×(1.23 kg/m^3)×0.002×(10/6×1.82 m/s)^3×(6.290×10^{7} s/2-year)=1.04×10^{9} J/2-year. [d] Rain energy=(area)×(rainfall)×(evapotranspiration)×(density)×(Gibbs free energy)=(240 m^2)×(1.180 m/2-year)×(3.00 m/2-year)×(1000 kg/m^3)×(4940 J/kg)=4.20×10^{9} J/2-year. [e] Topsoil loss energy=2×(area)×(soil loss rate)×(organic matter content)×(5400 kcal/kg)×(4186 J/kcal)=2×(240 m^2)×0.85×1.46%×(5400 kcal/kg)×(4186 J/kcal)=1.35×10^{8} J/2-year. The erosion rate is based on Li (2011). [f] Average value between China EMR in 2012 (Wang and He (2015) with the baseline of 9.44×10^{24} sej/year. UEVs adopted from those papers are multiplied by 1.61 for conversion to the new baseline of 15.20×10^{24} sej/year) and China EMR in 2013 (Liu *et al.* (2015) with the baseline 15.20×10^{24} sej/year)

Table 2 Emergy evaluation table of the CCP production model

No.	Item	RT	Raw data	UEV[a]	Solar emergy (sej)
	Renewable natural resources (*R*)				
1	Sunlight (J)	1.00	1.55×10^{12}	1.00	1.55×10^{12}
2	Wind, kinetic (J)	1.00	1.04×10^{9}	2.35×10^{3}	2.44×10^{12}
3	Rain (J)	1.00	4.20×10^{9}	2.93×10^{4}	1.23×10^{14}
	Total renewable natural resources				1.27×10^{14}
	Non-renewable resource (*N*)				
4	Net topsoil loss (J)	0	1.35×10^{8}	1.19×10^{5}	1.60×10^{13}
	Total non-renewable resource				1.60×10^{13}
	Purchased resource (*F*)				
5	Machinery depreciation (USD)	0.05	30.20	3.67×10^{12}	1.11×10^{14}
6	Fuel (J)	0.05	9.56×10^{7}	1.06×10^{5}	1.01×10^{13}
7	Film (g)	0.05	5.00×10^{3}	6.10×10^{8}	3.05×10^{12}
8	Herbicide (USD)[a]	0.05	4.75	3.67×10^{12}	1.74×10^{13}
9	Compound (g)	0.05	6.40×10^{3}	4.90×10^{9}	3.14×10^{13}
10	Land rent (USD)	0.05	68.60	3.67×10^{12}	2.52×10^{14}
11	Labor (J)	0.60	4.04×10^{7}	2.79×10^{6}	1.13×10^{14}
12	Corn seeds (USD)	0.05	8.02	3.67×10^{12}	2.94×10^{13}
	Total purchased emergy				5.66×10^{14}
	Total renewable purchased emergy (F_R)				9.03×10^{13}
	Total renewable purchased emergy (F_N)				4.76×10^{14}
	Total emergy input (*U*)				7.09×10^{14}
	Output (*Y*)				
13	Straw (J)		6.06×10^{5}	6.59×10^{8}	3.99×10^{14}
14	Corn (J)		4.18×10^{5}	1.98×10^{9}	8.26×10^{14}
	Total output emergy				1.23×10^{15}

RT: renewability factors. [a] Average value between China EMR in 2012 (Wang and He (2015) with the baseline of 9.44×10^{24} sej/year. UEVs adopted from those papers are multiplied by 1.61 for conversion to the new baseline of 15.20×10^{24} sej/year) and China EMR in 2013 (Liu *et al.* (2015) with the baseline 15.20×10^{24} sej/year)

In CCP, the total emergy input was 7.09×10^{14} sej/2-year, which consisted of *R*, *N*, F_R, and F_N, each constituting 17.90%, 2.25%, 12.73%, and 67.12%. respectively. The F_N made the largest contribution to total input in the CCP model, with the primary components being labor (9.46%), land rent (50.22%), and machinery depreciation (22.07%). Corn was the emergy yield entering the market and straw was reserved as fodder for overwintering livestock.

In the PWR production model, the total emergy input was 7.63×10^{14} sej/2-year higher than that of the CCP production model. The inputs to PWR were made up of *R*, *N*, F_R, and F_N, each taking up 16.64%, 2.09%, 12.30%, and 68.97%, respectively. As with CCP, F_N made the largest contribution to total emergy input in the PWR model. The components of F_N were also similar to those of the CCP production model, except that irrigation water was added and it constituted 1.09%. The pea residue and nitrogen fixation were used as feedback for growing wheat. Peas and wheat were the output emergy entering the market, and the pea and wheat straw were reserved as fodder for overwintering livestock.

In RGICF, the total emergy input was 1.34×10^{15} sej/2-year, which was 6.32×10^{14} sej/2-year and 5.78×10^{14} sej/2-year higher than that of CCP and PWR, respectively. The inputs to RGICF consisted of *R*, *N*, F_R, and F_N, each taking up 9.47%, 1.19%, 31.29%, and 58.05%, respectively. This model was different from the CCP and PWR systems, however, because F_N made a lower contribution to total emergy input, which in this case mainly consisted of land rent (30.71%), the non-renewable portion of fodder (19.27%), and machinery depreciation (13.50%). However, the contribution of *R* to total emergy input in RGICF (9.47%) was lower than that of CCP

Table 3 Emergy evaluation of the PWR production model

No.	Item	RT	Raw data	UEV[a]	Solar emergy (sej)
	Renewable natural resources (*R*)				
1	Sunlight (J)	1.00	1.55×10^{12}	1.00	1.55×10^{12}
2	Wind, kinetic (J)	1.00	1.04×10^{9}	2.35×10^{3}	2.44×10^{12}
3	Rain, chemical (J)	1.00	4.20×10^{9}	2.93×10^{4}	1.23×10^{14}
	Total renewable natural resources				1.27×10^{14}
	Non-renewable resource (*N*)				
4	Net topsoil loss (J)	0	1.35×10^{8}	1.19×10^{5}	1.60×10^{13}
	Total non-renewable resource				1.60×10^{13}
	Purchased resource (*F*)				
5	Irrigation water (J)	0	1.93×10^{8}	2.97×10^{4}	5.71×10^{12}
6	Machinery depreciation (USD)[a]	0.05	30.20	3.67×10^{12}	1.11×10^{14}
7	Fuel (J)	0.05	9.56×10^{7}	1.06×10^{5}	1.01×10^{13}
8	Pea seed (USD)	0.05	15.90	3.67×10^{12}	5.82×10^{13}
9	Herbicide (USD)	0.05	2.25	3.67×10^{12}	8.25×10^{12}
10	Compound (g)	0.05	6.40×10^{3}	4.90×10^{9}	3.14×10^{13}
11	Land rent (USD)	0.05	68.60	3.67×10^{12}	2.52×10^{14}
12	Labor (J)	0.60	4.12×10^{7}	2.79×10^{6}	1.15×10^{14}
13	Wheat seeds (USD)	0.05	8.02	3.67×10^{12}	2.94×10^{13}
	Total purchased emergy				6.20×10^{14}
	Total renewable purchased emergy (F_R)				9.39×10^{13}
	Total renewable purchased emergy (F_N)				5.26×10^{14}
	Feedback emergy in the system (R_2)				
14	Nitrogen fixation (J)		1.58×10^{3}	1.03×10^{10}	1.62×10^{13}
	Total feedback emergy in the system				1.62×10^{13}
	Total emergy input (*U*)				7.63×10^{14}
	Output (*Y*)				
15	Wheat straw (g)		4.13×10^{9}	1.10×10^{5}	4.55×10^{14}
16	Pea straw (g)		1.10×10^{9}	1.43×10^{5}	1.58×10^{14}
17	Pea (g)		6.27×10^{8}	3.83×10^{5}	2.40×10^{14}
18	Wheat (g)		2.31×10^{9}	2.98×10^{5}	6.90×10^{14}
	Total output emergy				1.54×10^{15}

RT: renewability factors. [a] Average value between China EMR in 2012 (Wang and He (2015) with the baseline of 9.44×10^{24} sej/year. UEVs adopted from those papers are multiplied by 1.61 for conversion to the new baseline of 15.20×10^{24} sej/year) and China EMR in 2013 (Liu *et al.* (2015) with the baseline 15.20×10^{24} sej/year). UEVs reference for respective row number: 14 refer to Xi and Qin (2009) with the baseline of 9.26×10^{24} sej/year (UEVs adopted from those papers are multiplied by 1.64 for conversion to the new baseline of 15.20×10^{24} sej/year); 15, 16, 17, and 18 refer to Wu *et al.* (2013) with the baseline of 9.26×10^{24} sej/year (UEVs adopted from those papers are multiplied by 1.64 for conversion to the new baseline of 15.20×10^{24} sej/year)

(17.90%) and PWR (16.64%). In this model, weeds were not a hazard to agricultural production, but rather food for the geese; the geese in turn dropped their feces onto the field, which became feedback for the growth of corn and weeds. Finally, the emergy of corn, straw, and geese were the outputs that could be sold in the market.

3.2 Emergy indices of the three production systems

The emergy-based indicators, which were used to assess production efficiency, environmental status, sustainability, and product safety, showed differences among the three production systems in terms of EYR, ESR, ELR, ESI, FYE, and EIPS as listed in Table 4. Owing to the fact that the RGICF production model relied mainly on purchased resources, the EYR and ESR were 0.66 and 0.11 lower than for CCP, respectively, and 0.99 and 0.08 lower than for PWR, respectively. ELR denotes the impact of the productive process on the environment with lower values indicating a smaller impact. The impact of RGICF (1.45) on the environment was lower than that of CCP (2.26) and PWR (2.46). The ESI of RGICF was 1.07 and 1.02 times higher than CCP and PWR, respectively, indicating that RGICF performed better in systematic sustainability than CCP and PWR. RGICF

Table 4 Comparison of main emergy indicators of the different production systems

Item	Formula	CCP	PWR	RGICF
Emergy yield ratio, EYR	$EYR=Y/(F_N+F_R)$	2.16	2.49	1.50
Emergy self-supporting ratio, ESR	$ESR=(R+N)/U$	0.22	0.19	0.11
Environment loading ratio, ELR	$ELR=(F_N+N)/(F_R+R)$	2.26	2.46	1.45
Emergy sustainable indices, ESI	ESI=EYR/ELR	0.96	1.01	1.03
Feedback ratio of yield emergy, FYE	$FYE=R_2/(F_N+F_R)$	0	0.03	0.03
Emergy index of product safety, EIPS	$EIPS=1-C/(F_N+F_R)$	0.91	0.94	0.97

R: emergy input of renewable natural resources; N: sum of non-renewable natural resource emergy; F_N: total of purchased non-renewable resource emergy; F_R: total of purchased renewable resources emergy; R_2: feedback emergy in the system; U: total emergy input; Y: total emergy yield; C: sum of herbicide and fertilizer emergy

and PWR had the same FYE, but system FYE was not shown in the CCP model. The EIPS values were low in all three systems, suggesting that the products were not safe, particularly in CCP and PWR.

3.3 Evaluation of economic benefits under different production systems

Table 5 gives financial information for the RGICF, PWR, and CCP production systems. The largest economic input in RGICF was feed (30.52%), followed by land rent (15.69%) and supporting labor (13.08%). In PWR, land rent (34.93%) was the largest economic input, followed by machinery depreciation (23.08%), supporting labor (11.64%), and chemical fertilizer (11.18%). Similarly, in the CCP production model, land rent (33.77%) was the largest cost, followed by machinery depreciation (22.31%), supporting labor (11.26%), and chemical fertilizer (10.81%). The RGICF production model received the largest economic net income being 2.36 times higher than that of the PWR system and 2.52 times higher than that of CCP; however, it also required the largest economic investment being 2.23 and 2.15 times higher than those of PWR and CCP, respectively. Owing to the considerable economic output of the RGICF system (2.25 and 2.21 times higher than those of PWR and CCP, respectively), the ratio of output to input was 0.03 and 0.04 times than those of PWR and CCP, respectively.

Table 5 Comparison of the economic benefits (USD/ha) of different production systems during the 2012 and 2013 growing season

Item	RIGICF	PWR	CCP
Input			
Water	1.15	71.39	
Feed	3703.70		
Fuel	34.88	34.88	34.88
Film	444.44		444.44
Chemical fertilizer	609.52	609.52	609.52
Machinery depreciation	1258.33	1258.33	1258.33
Nylon net	357.14		
Heating device	52.91		
Herbicide		198.41	396.83
Medicine	79.37		
Land rent	1904.76	1904.76	1904.76
Hydropower	158.73		
Labor	1587.30	634.92	634.92
Corn seeds	357.14		357.14
Pea seed		595.24	
Wheat seed		145.503	
Baby geese	1587.30		
Total	12136.69	5452.96	5640.83
Output			
Pea		2936.51	
Wheat		3809.52	
Geese	8761.90		
Corn	6428.57		6851.85
Total	15190.48	6746.03	6851.85
Output/Input	1.25	1.24	1.21
Gross income	15190.48	6746.03	6851.85
Net income	3053.79	1293.07	1211.02

4 Discussion and conclusions

4.1 Comparison of production efficiencies under the different courtyard agriculture models

Production efficiency is based on external input, resource use efficiency, and output. EYR measures the ability of a production process to exploit local resources that are fed back from outside (Brown and Ulgiati, 1997). In this study, the input emergy for raising geese was found to be 2.28 times greater than that of CCP. The additional input emergy required to add geese to the RGCIF production model included baby geese, feed, and extra labor, implying that this model had the largest emergy input of the three courtyard agriculture models examined. As a result, the EYR of the RGICF model was lower than that of CCP and PWR. The resource use efficiencies of PWR and RGICF were higher than that of CCP because the internal emergy recycling of PWR and RGICF improved the resource use efficiency in these systems. The same feedback ratio of yield emergy value occurred in the PWR and RGICF models. The emergy output of geese from the RGICF model was the largest of the three courtyard agriculture models, and CCP demonstrated the lowest emergy output. In summary, we found that PWR had a slightly higher production efficiency than CCP, and RGICF had the lowest production efficiency.

4.2 Comparison of environmental benefits and sustainability under different courtyard agriculture models

A sustainable courtyard agriculture model focuses not only on economic benefit but also on environmental concerns. In this study, we used emergy-based indicators such as the ELR and ESI to evaluate the environmental load and sustainability of the agricultural production systems. ELR is directly related to consumed renewable resources and is an indicator of the pressure of the production process on the local environment. Brown and Ulgiati (1997) showed that ELR values less than 2 indicate that the production process has a moderate impact on the local environment. In this study, ELR was less than 2 in the RGICF production patterns; however, ELRs in CCP (2.16) and PWR (2.49) were higher than 2, suggesting that the RGICF had a less damaging impact on the local environment.

ESI is an aggregate indicator of yield and environmental load for measuring the sustainability of a production process. ESI values from 1 to 10 show that the system has excellent sustainability. Brown and Ulgiati (1997) suggested that ESI values less than 1 indicate a high-consumption system, whereas values greater than 20 show an undeveloped system. The ESI values of RGICF and PWR were 1.03 and 1.01, respectively, which suggests that these production models have superior long-term sustainability. In contrast, CCP had an ESI value less than 1, which suggests that this production pattern is not suitable for long-term sustainable development.

In the RGICF method, weeds were controlled naturally through feeding and trampling by geese rather than the application of herbicide. Thus, weed growth was limited and high weed diversity was maintained (Sha *et al*., 2014; Zhang Y.Y. *et al*., 2014b). The beneficial functions of weed diversity have been reported in many regions; these include prevention of soil erosion, providing refuge for predatory insects, and providing overwintering food for higher trophic level species (Wyss, 1996; Chen *et al*., 2000). In contrast, non-renewable purchased resources such as herbicide and irrigation water were applied in the CCP and PWR production systems to increase yields, and as a result, the ELR was increased and ESI was decreased in these systems.

4.3 Comparison of economic benefits under different courtyard agriculture models

Economic analysis based on market price is presented in Table 5. The PWR production model, which is the traditional courtyard agriculture model in Tibet Autonomous Region, China, had the lowest output among the three models. Therefore, to some degree, this traditional method may need to be altered because it does not safeguard the sensitive plateau ecological environment, and it has low economic benefits (TSY, 2007). Corn planting is a more popular cultivation choice in recent years because it produces a high economic return on investment and produces more straw for overwintering livestock. However, CCP is also unsuitable for the ecology of the sensitive plateau environment because of the considerable requirement for non-renewable resource inputs. The greatest economic input and output were provided by the RGICF production model. Generally, high economic inputs indicate a greater risk for production. However, the production risks of RGICF can be neglected owing to the characteristics of courtyard agriculture (i.e., home courtyard agriculture is conducive to controlling pests and disease, and raising geese on a small-scale level appears to promote a high survival rate among baby geese).

In the RGICF production model, the output of the corn planting component was 423.28 USD/ha lower than that of CCP production model. The disturbance to the cropping system from grazing and trampling by geese may be one of the main reasons for the decrease in the corn yield in this production model. The geese not only consumed the weeds, but also preferentially ate the bottom crop leaves. The photosynthesis of corn may have declined because of this grazing and subsequent reduced leaf area, which would decrease corn yield. In addition, competition with weeds for resources, such as sunlight and nutrients, could affect corn yield. However, grazing and trampling by geese constrained the growth of the aboveground portion of the weeds, and thereby, the competition of weeds with corn for environmental resources could be limited. The reduction in corn yield was more than compensated for by the economic output of geese, thus acquiring larger economic benefits (3053.79 USD/ha) than the PWR (1293.07 USD/ha) and CCP (1211.02 USD/ha) production models.

In conclusion, our results suggest that the RGICF model is advantageous, and it provides higher environmental benefits than the CCP and PWR systems.

Compliance with ethics guidelines

Fa-chun GUAN, Zhi-peng SHA, Yu-yang ZHANG, Jun-feng WANG, and Chao WANG declare that they have no conclict of interest.

This article does not contain any studies with human or animal subjects performed by any of the authors.

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中文概要

题　目：西藏三种庭院生产体系的能值评价

目　的：利用能值方法评价西藏三种庭院生产体系的生产效率、环境效益、可持续性以及经济效益。

创新点：利用能值方法，首次对近年流行的新型农牧一体化生产模式（“玉米田养鹅”），以及西藏常规庭院生产体系“豌豆–小麦轮作”和“常规玉米连作”进行生态与生产效益的全面评价，明确适宜西藏可持续发展的庭院生产技术体系。

方　法：以两年（2012 和 2013）作为时间单元，记录期间各庭院生产体系物质的投入和产出。各生产体系中所有投入和产出的物质与各物质相对的转化系数即单位能值价值（UEV）相乘转换为太阳能值（sej），各物质的 UEV 统一全球驱动能值在 15.20×10^{24} sej/year 的基准上。利用“可新比例”划分各投入物质的可更新和不可更新的部分，并计算相应的能值指标（能值产出率、能值自给率、环境负载率、可持续性指标以及农产品安全指标等），从而通过能值指标和经济效益的分析来评价各庭院生产体系的生态与经济效益。

结　论：本研究中“玉米田养鹅”具有卓越的生态–经济效益，“豌豆–小麦轮作”次之，而“常规玉米连作”可持续性低且环境负载较大。

关键词：庭院农业；玉米田养鹅；传统玉米种植；豌豆–小麦轮作；能值；可持续性