



An assessment of energy, energy, and cost-benefits of grain production over 6 years following a biochar amendment in a rice paddy from China

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Abstract

Biochar soil amendment had been increasingly advocated for improving crop productivity and reducing carbon footprint in agriculture worldwide. However, the long-term benefits of biochar application with farming systems had not been thoroughly understood. This study quantified and assessed energy, energy, and economic benefits of rice and wheat production throughout 6 rotation years following a single biochar amendment in a rice paddy from Southeastern China. Using the data from farm inventory, the quantified energy indices included grain outputs, unit energy value, and relative percentage of free renewable resources, environmental loading ratio, energy yield ratio, and energy sustainability index (ESI). The results indicated contrasting differences in these energy values between biochar-amended and unamended production systems over the 6 years. The overall energy efficiency of rice and wheat productions in biochar-amended system were higher by 11–28 and 15–47%, respectively, than that of unamended one of which the production being highly resource intensive. Moreover, ESI on average was 0.46 for rice and 0.63 for wheat in amended system, compared to 0.35 for rice and 0.39 for wheat in unamended one. Furthermore, over the 6 years following a single application, the ESI values showed considerable variation in the unamended system but consistently increasing in the amended system. Again, the biochar-amended system exerted significantly higher energy and economic return than the unamended one. Nonetheless, there was a tradeoff between rice and wheat in grain yield and net economic gain. Overall, biochar amendment could be a viable measure to improve the resilience of grain production while to reduce resource intensity and environment impacts in paddy soil from China.

Keywords Biochar soil amendment · Energy analysis · Field experiment · Rice paddy · Rice and wheat production · Ecological benefits · Resource efficiency

Introduction

It had become an increasingly critical challenge to feed the growing population with decreasing resource supplies while

diminishing environmental impacts in world agriculture. Biochar, a carbon-rich solid material produced via the pyrolysis of waste biomass, had been increasingly recommended for use as soil amendment for enhancing soil functions and quality for crop productivity enhancement and emission reduction in agriculture (Lehmann et al. 2015; Zhang et al. 2016). Although the long-term persistence of biochar in soil varied in wide range, its turnover could be considerably slower compared to other plant-derived organic inputs to soil (Singh et al. 2012). The production and application of biochar might provide a sound measure to reduce atmospheric CO₂ concentrations through long-term sequestration of plant photosynthesized carbon into recalcitrant carbon stock (Shepherd 2009). Therefore, biochar production from bio-wastes and use as amendment to agricultural soils could have a great potential to mitigate climate change while to improve crop production in global agriculture (Singh et al. 2010; Woolf et al. 2010). Indeed, such double effects had been widely

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reported in short-term field experiments (Singh et al. 2010; Zhang et al. 2010). And biochar use is known to alleviate the soil degradation due to intensive cultivation and soil contamination, in most of agricultural lands (Zhang et al. 2011). Yet, understanding the long-term benefits of biochar use in agriculture had been challenged with limiting field studies that had sustained for multiple years (Zhang et al. 2016).

For practical application of biochar, the cost-effectiveness had been often in a debt for the high cost of a single amendment using large amount of biochar (Clare et al. 2014). Moreover, household farmers managing small-scale farmlands were often difficult to make decision to invest on biochar use. Large amount of biochar use in a single amendment would confront the profitability of agricultural production for adoption of biochar technology and would be strongly dependent on its costs and benefits (Abiven et al. 2014). As a part of low carbon economy strategy, the commercial production of biochar from various types of biomass feedstock with large-scale pyrolysis systems had been granted in China (NDRRC 2017). Recently, biochar-based inorganic/organic fertilizers had been put into marketing as novel agro-chemicals as a paradigm shifting sole chemical fertilizer use in China (General Office of the Ministry of Agriculture 2017). Thus, an evaluation of the long-term ecological and economic benefits of using biochar in agriculture had become an urgent need before upscaling biochar commercialization.

As an approach to combine energetics and systems ecology, a framework of energy analysis together with a quantification protocol was first developed in the 1980s (Odum 1996). Energy analysis addressed the drawbacks of conventional energy analysis and characterized variable energy quantified in one physical basis of solar energy equivalents. In addition, it considered aspects of energy forms that were frequently overlooked in other approaches evaluating such as environmental input, ecosystem services, and labor. A higher energy value was related to a greater use of material, energy, or labor in its creation. Alternatively, product's value of energy was higher if more energy flow was dissipated. Since the 1990s, this methodology had been widely adopted to assess the resource use, environmental impact, and overall sustainability with productivity of agricultural systems (Chen et al. 2006; Diemont et al. 2006; Zhang et al. 2012b). In particular, as one of the key components of the agricultural ecosystem, cereal production had been compared in terms of energy values for its sustainability (Ghaley and Porter 2013; Li and Yan 2012; Lu et al. 2010).

With increasing crop intensification and excessive-inputs, grain yield of China had been continuously increased over the last decades, causing significant costs of non-renewable resources, land degradation, and environmental pollution (Zhang et al. 2013b). Rice-wheat rotation system had been conventionally a prevailing farming system of Southeastern China (Frolking et al. 2002). Field tests had shown positive

effects of biochar on grain production, GHG reduction, as well as soil fertility in such system (Zhang et al. 2013a). While carbon footprint could characterize carbon reduction by biochar amendment in rice agriculture (Yan et al. 2015), how sustainable and cost-efficient the biochar-amended system could be had not yet been clear in terms of energy assessment.

We hypothesized that biochar-amended soil and production system could have better performance in terms of efficiency and sustainability, compared to conventional system, mainly by improving soil quality and resource use. Thus, this study is to quantify and characterize the changes in values of energy and cost-benefits of rice-wheat production system under biochar soil amendment. For this, we use a 6-year long pilot field trial of biochar amendment in a rice paddy under rice-wheat double cropping system from Jiangsu, China. We aim to address if biochar soil amendment could be a smart measure for sustainable agriculture in paddy soils from Southeastern China.

Materials and methods

Experimental system

The assessed system was a rice-wheat rotation system, typical for agricultural in Southeastern China. The site was located in Jingtang Village (31° 24' N and 119° 41' E), Yixing Municipality of Jiangsu Province, China. Rice had been cultivated in the area for a thousand years, which was traditionally one of the most productive regions of rice agriculture of China (Xu 2001). Derived from lacustrine deposit, the soil was classified as an entic Hapudept with USDA Soil Taxonomy (Soil Survey Staff 1994) and a hydroagric Stagnic Anthrosol with Chinese Soil Taxonomy (Gong 1999). A subtropical monsoon climate prevailed in the area with a mean annual temperature of 15.7°C and 1177 mm of precipitation over 2009–2015. The chemical properties of the topsoil (0–15 cm depth) sampled and measured in 2009 were as follows: pH (H₂O), 6.5; soil organic carbon (SOC), 2.4%; total soil nitrogen, 0.18%; bulk density, 1.01 g/cm³; and a clay content, 39%.

The system had been tested with biochar amendment to the rice paddy since 2009. As reported by Zhang et al. (2010, 2012a, 2013a), the soil was amended once with biochar at 20 t/ha after wheat harvest in 2009, in comparison to the conventional receiving no biochar. The biochar was produced by the Sanli New Energy Company of Henan Province, via pyrolysis of wheat straw at temperature in a range of 350–550 °C in a continuous vertical kiln, with 35% of the feedstock converted to biochar. The biochar was ground to pass through a 2-mm sieve before field use. Biochar mass was spread over soil surface and homogenized to keep consistency in the plot. The biochar had a bulk density of 0.24 g/cm³ and specific

surface of 16.7 m²/g. The organic matter in the biochar was dominated by aromatic carbon. Other physicochemical properties of the biochar used are provided in Table 1.

The farm production under the rice-wheat rotation system had been kept consistent since 2009. Rice (*Oryza sativa* L., cv. “Wuyunjing 7”) seeds were directly sowed in early June and harvested in late October. Following rice harvest, winter wheat (*Triticumaestivum* Linn.) seeds were sowed in early November and harvested in late May in the following year. Information of crop performance and management throughout the 6 years since 2010 are provided in the [Supplementary material](#).

Emergy analysis

Emergy baseline

The 15.83E+24 sej/year planetary (Odum et al. 2000) baseline was applied in this study, with all cited unit emergy values and comparative results transformed in accordance to this baseline, if they were not originally reported based on it.

Emergy analysis protocol

Emergy was defined as the sum of solar energy necessary, indirectly or directly to make a product or a service, expressed in solar equivalent. The major components and interactions for each of the cropping practices are outlined in Fig. 1, as proposed by Odum (1996). The flows of inputs and outputs crossing the boundary of system had been quantitatively accounted. The inputs considered here were of both environmental inputs and economic inputs for grain production up to harvest gate, so as to exclude the resources for output (grain) transport. In detail, inputs were the sum of local/free renewable resources (*R*), local/free non-renewable resources (*N*), and purchased resources (*F*), which was categorized as the sum of emergy of a process. The value of *R* in emergy analysis included rain, wind, and sun radiation; the *N* value included irrigation water; and *F* included inputs associated with fuel, electricity, fertilizer, machinery, seed, agro-chemicals, and labor purchased for the production (see the [Supplementary material](#) and [Appendices](#)).

In this study, rain and wind were regarded as derivatives of sun radiation in emergy analysis, and thus, only the flow with the highest renewable could be taken into account in the sum of emergy (Odum 1996). We counted these values for individual crop seasons and production stages ([Supplement](#)

[tables](#)). Next, the different inputs in different units were multiplied by the transformity coefficient to normalize into an emergy value in unit of sej, using Eq. (1):

$$E_m = \sum f_i \times tr_i, \quad i = 1, \dots, n \tag{1}$$

where E_m is the solar emergy in *sej*, f_i is the *i*th input, and tr_i is the transformity of the *i*th flow.

Emergy evaluation indicators

After all the component emergy flows of a system were aggregated, emergy evaluation indicators could be then calculated to assess the different grain production systems associated with economic and ecological efficiencies as indicators of sustainability (Chen et al. 2006; Ghaley and Porter 2013). Emergy-based indices were then estimated for total emergy input (*U*), grain output (*Y*), unit emergy value (UEV), percentage of renewable resources fraction (Rewability), environmental loading ratio (ELR), emergy yield ratio (EYR), and emergy sustainability index (ESI). In emergy studies, renewability provided a common criterion for sustainability, with a higher value identifying a higher utilization of local renewables and thus less environmental impacts. Further, EYR indicated the efficiency of grain production process in utilizing materials (*M*) and services (*S*). It indicated the ability to exploit local resources, and the higher value of EYR indicates higher production efficiency and is conducive to wider economy. Moreover, ELR values were used to characterize a load on the environment, and the higher the value of this parameter, the greater is the ecosystem stress owing to the process. Finally, the ESI was an integrated measure, considering both economic and ecological compatibility. This index indicates whether a production process or activity provides an appropriate contribution to the users without a high environmental stress (Brown and Ulgiati 1997). The larger the ESI, the more compatible and sustainable is the production process over time.

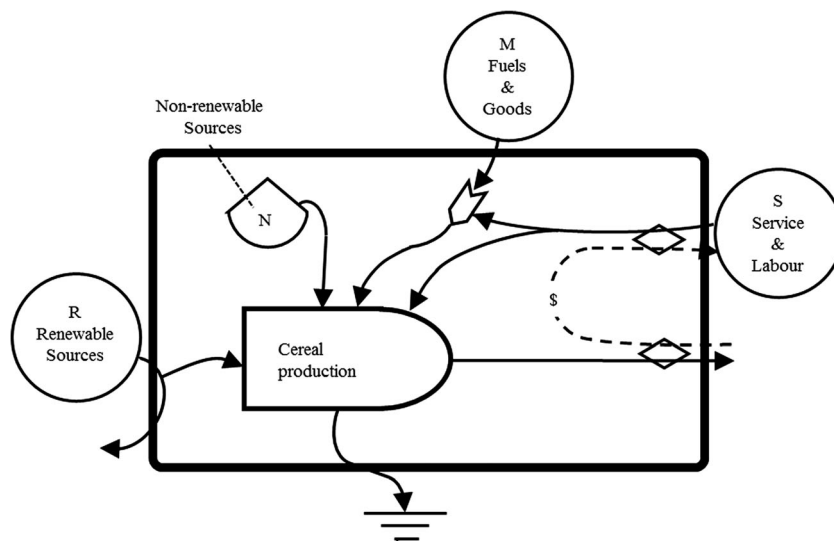
In this study, *Y* was the total output of a system (in joules), which was the sum of the harvested grain produced. Total emergy input (*U*, in sej) was estimated as the sum of renewable resource (*R*), non-renewable resource (*N*), and purchased inputs (*F*) in a production system. As already noted, the UEV (in sej/J) measured how much the total emergy inputs used in the creation of a product to produce one unit of *Y* (Odum 1996), using Eq. (2):

$$\text{Unit emergy value (UEV)} = U/Y \tag{2}$$

Table 1 Selected characteristics of the wheat straw biochar used in this study

pH (H ₂ O)	CEC (cmol/kg)	TOC (g/kg)	N (g/kg)	P (mg/kg)	K (g/kg)	NH ₄ ⁺ (mg/kg)	NO ₃ ⁻ (mg/kg)	Mg (g/kg)	Ca (g kg)
10.03	40.78	467.21	10.35	55.63	15.87	5.51	6.71	0.6	10.6

Fig. 1 Resumed diagram of agricultural production system



Subsequently, renewability was estimated as the percentage of renewables to total resources directly and indirectly exploited for a production within the system, which was calculated using Eq. (3):

$$\text{Renewability} = R / (R + N + F) \quad (3)$$

In energy analysis, the EYR was calculated as the ratio of the total emergy value of output of the production system (U) to the purchased resources (F) for material inputs (M) and services (S) provided for the production by using Eq. (4):

$$\text{Emergy yield ratio (EYR)} = U / (F_M + F_S) \quad (4)$$

For measuring the environment impact on of the system, the ELR was estimated as the ratio of total emergy of non-renewables (N) and purchased input (F) to the emergy of renewable resources by using Eq. (5):

$$\text{Environment load ratio (ELR)} = (M + S + N) / R \quad (5)$$

Finally, the ESI was calculated as the ratio of the environmental yield ratio to the ELR by using Eq. (6):

$$\text{Emergy sustainable indices (ESI)} = \text{EYR} / \text{ELR} \quad (6)$$

Mover, the relative impacts of variations in input amounts and transformities were analyzed using a sensitivity analysis to quantify the impacts of varying the emergy inputs. According to Odum and Odum (2000), the effect of halving and doubling the mean values of emergy upon the indicators was calculated.

Energy and economic analysis

The net energy gain, specific energy, energy productivity, and energy use efficiency (energy ratio) were, respectively, quantified based on the energy coefficients (Supplementary

material), by using the following equations (Demircan et al. 2006):

$$\text{Net energy} = \text{Energy output} - \text{Energy input} \quad (7)$$

$$\text{Specific energy} = \text{Energy input} / \text{Grain output} \quad (8)$$

$$\text{Energy productivity} = \text{Grain output} / \text{Energy input} \quad (9)$$

$$\text{Energy use efficiency} = \text{Energy output} / \text{Energy input} \quad (10)$$

Furthermore, grain production was economically analyzed, and the benefit-cost ratio and net profit were quantified. The benefit-cost ratio was expressed as a ratio of the gross value divided by the overall cost of process per hectare. The net economic return was quantified by deducting the overall cost from the gross value of production per hectare.

Data source

In this study, all data, including inputs and outputs of these production system, were obtained using two approaches. First, a questionnaire inventory was conducted by interviewing farm owners and managers for obtaining information regarding the input and output data of the production system. Second, robust measurement data of soil and plant as well as environmental properties were obtained and synthesized from the field studies performed by the author's institute over the experimental period.

In addition, data of environment resources, including rainfall, wind, solar radiation, and irrigation water, were accessed from the China Meteorological Data Service Center (CMA Meteorological Data Center 2016) and from the data archive in the authors institute for the site. Soil and crop data were retrieved from our filed studies throughout 2010–2015. All machinery input used in the grain production process were transformed into annual flows on the basis of the estimated useful life of the farm machine, which was expected to be 10 years. The energy content data of resource in the emergy

evaluation were quantified by using formulas derived by Odum (1996) and on the basis of energy equivalents reported by Chen (2011). Cultivation costs under different treatments were calculated based on market values available from Jiangsu Province. The input costs included those for fertilizers, pesticides, seeds, and irrigation, as well as the hiring charges of agricultural machines and human labor. The original survey data of the system is given in the [Supplement information](#) separately. All the flows of money of Chinese Yuan were exchanged to US\$ by using the ratio of 6.25 Yuan/US\$ for better understanding.

Calculation and statistics

All data processing and calculations were performed using the EXCEL, Windows Office 2003. Values are given as the average or mean of the crop plots or production years.

Results

Productivity and agricultural input

Pooled data (Table 2) of inputs and outputs from farm inventory are shown for interpretation. Apparently, biochar amendments resulted in a yield increase of rice and wheat by 9–13 and 17–36%, respectively, over the conventional system during 2010–2014. Interestingly, grain yield of rice and wheat was increased by 7 and 18%, respectively, even in 2015, the

sixth year following a single biochar amendment in 2009. Further, such yield increase was greater for wheat than for rice throughout the 6 years of experiment.

With biochar amendment, plant N concentration was decreased by 3 and 38% on average for rice and wheat crop, respectively, during 2012 to 2015. Similarly, plant P and K concentration were also observed to reduce at varying degrees. For crop protection, amount of the pesticides used by farmers was smaller in biochar-amended system than in un-amended one. Particularly, the pesticide use over the rice-growing seasons was reduced by 45% in biochar-amended system in 2014, when the incidence and severity of rice blast disease was the highest in Jiangsu Province for the last 30 years (Pesticide Express 2015). Also, rice in the amended system was observed more collapse-resistant in 2014 when collapse normally happened to rice production due to heavy storms. This directly contributed to higher harvested yield and less consumption of mechanical energy input in biochar-amended paddy compared to the conventional one.

Emergy flows and overall characterization of crop production

According to the energy system characterization diagram (Fig. 1), the basic information of emergy analysis of the rice and wheat production systems was created and provided in the [Appendix Tables](#). The emergy components calculated from the collected data and by using Eq. (1) are shown in Table 3. The total emergy input to the rice-wheat production was in a

Table 2 Farm inventory of the resource inputs into crop production over the years since biochar amendment

Year	CROP Season	Resource input (kg/ha)								Fuel (kg/ha)		Labor (h/ha)		Yield (t/ha)	
		Nf		Pf		Kf		Ps		NB	BA	NB	BA	NB	BA
		NB	BA	NB	BA	NB	BA	NB	BA						
2010	Rice	300	300	204	204	204	204	8.48	5.88	41.36	35.73	217.13	141.4	7.63	8.30
	Wheat	300	300	60	60	60	60	1.54	1.54	17.02	17.02	69.38	69.38	4.20	4.90
2011	Rice	300	300	125	125	125	125	13.37	8.27	41.36	35.73	217.13	141.4	7.57	8.25
	Wheat	300	300	60	60	60	60	2.06	2.06	17.02	17.02	69.38	69.38	4.72	6.12
2012	Rice	300	290	125	33	125	66	10.87	6.87	41.36	35.73	217.13	133.9	7.62	8.28
	Wheat	300	186	60	24	60	48	1.91	1.91	17.02	17.02	69.38	61.88	4.84	6.50
2013	Rice	300	290	125	33	125	66	7.99	4.39	41.36	35.73	217.13	133.9	8.03	8.82
	Wheat	300	186	60	24	60	48	2.06	2.06	17.02	17.02	69.38	61.88	4.87	6.60
2014	Rice	300	290	125	33	125	66	11.46	6.26	44.67	35.73	221.63	133.9	7.33	8.31
	Wheat	300	186	60	24	60	48	2.81	2.81	17.02	17.02	69.38	61.88	4.80	6.25
2015	Rice	300	290	125	33	125	66	10.25	6.78	41.36	35.73	217.13	133.9	7.80	8.38
	Wheat	300	186	60	24	60	48	2.81	2.81	17.02	17.02	69.38	61.88	4.80	5.68

Other inputs included seed at 60 and 210 kg/ha and machinery steel at 3.55 and 0.78 kg/ha, respectively, for rice and wheat production. For rice production, water amount and power consumed for irrigation at was 3750/m³/ha and 222.75 J/ha, respectively. There were hardly changes in these inputs and thus considered consistent over years in this study

NB no biochar amendment, BA biochar amendment, Nf nitrogen fertilizer, Pf phosphate fertilizer, Kf potassium fertilizer, Ps pesticides

Table 3 Energy flows (sej/ha) of the crop systems over the years since biochar amendment

Year	Crop season	R		N		F _M		F _S		U		Y	
		NB	BA	NB	BA	NB	BA	NB	BA	NB	BA	NB	BA
2010	Rice	7.50E+14	7.50E+14	1.58E+14	1.58E+14	4.27E+15	4.20E+15	1.30E+14	8.46E+13	5.31E+15	5.19E+15	5.31E+15	5.19E+15
	Wheat	2.70E+14	2.70E+14	0.00E+00	0.00E+00	2.73E+15	2.73E+15	4.15E+13	4.15E+13	3.04E+15	3.04E+15	3.04E+15	3.04E+15
2011	Rice	1.43E+15	1.43E+15	1.58E+14	1.58E+14	3.68E+15	3.57E+15	1.30E+14	8.46E+13	5.39E+15	5.24E+15	5.39E+15	5.24E+15
	Wheat	7.97E+14	7.97E+14	0.00E+00	0.00E+00	2.73E+15	2.73E+15	4.15E+13	4.15E+13	3.57E+15	3.57E+15	3.57E+15	3.57E+15
2012	Rice	7.93E+14	7.93E+14	1.58E+14	1.58E+14	3.64E+15	2.78E+15	1.30E+14	8.01E+13	4.72E+15	3.81E+15	4.72E+15	3.81E+15
	Wheat	8.79E+14	8.79E+14	0.00E+00	0.00E+00	2.73E+15	1.75E+15	4.15E+13	3.70E+13	3.65E+15	2.67E+15	3.65E+15	2.67E+15
2013	Rice	1.00E+15	1.00E+15	1.58E+14	1.58E+14	3.60E+15	2.74E+15	1.30E+14	8.01E+13	4.89E+15	3.98E+15	4.89E+15	3.98E+15
	Wheat	7.65E+14	7.65E+14	0.00E+00	0.00E+00	2.73E+15	1.75E+15	4.15E+13	3.70E+13	3.54E+15	2.55E+15	3.54E+15	2.55E+15
2014	Rice	1.16E+15	1.16E+15	1.58E+14	1.58E+14	3.66E+15	2.77E+15	1.33E+14	8.01E+13	5.11E+15	4.16E+15	5.11E+15	4.16E+15
	Wheat	1.01E+15	1.01E+15	0.00E+00	0.00E+00	2.75E+15	1.75E+15	4.15E+13	3.70E+13	3.80E+15	2.79E+15	3.80E+15	2.79E+15
2015	Rice	1.22E+15	1.22E+15	1.58E+14	1.58E+14	3.63E+15	2.77E+15	1.30E+14	8.01E+13	5.14E+15	4.23E+15	5.14E+15	4.23E+15
	Wheat	1.17E+15	1.17E+15	0.00E+00	0.00E+00	2.75E+15	1.76E+15	4.15E+13	3.70E+13	3.96E+15	2.96E+15	3.96E+15	2.96E+15

NB no biochar amendment, BA biochar amendment, R renewable input, N non-renewable input, F_M purchased material, F_S purchased services, U total energy input, Y energy in grain yield harvested

range of 8.35E+15–9.09E+15 sej/ha/year for the unamended conventional system and of 6.47E+15–8.81E+15 sej/ha/year for biochar-amended one. For the rice-growing seasons only, the total energy input ranged from 4.72E+15 to 5.39E+15 sej/ha/year and 3.81E+15 to 5.24E+15 sej/ha/year, respectively, in unamended and amended system, both accounting for 59% of the total input for the whole rice and wheat rotation. Total energy input in rice production in the first 2 years following biochar application was 19% lower for the subsequent years, and was slightly lower by 2–3% in biochar-amended system than in unamended one. For the wheat-growing seasons only, the total energy input ranged from 3.04E+15 to 3.96E+15 sej/ha/year and 2.55E+15 to 3.57E+15 sej/ha/year in the unamended and amended system. Moreover, the total energy inputs for wheat production were lower by 25–28% in biochar-amended system than in unamended one since 2012. It is clear that rice production consumed more non-renewable resources and energy than wheat within the whole rice-wheat rotation production.

In our study, the quantity of renewable resources was similar for both grain production systems, as that for the biochar-amended and unamended rice paddy located in the same experimental farm and had the same acreage. Constituting the bulk of the renewable energy flows into crop production, the rainfall input ranged from 7.50E+14 to 1.43E+15 sej/ha/year and from 2.70E+14 to 1.17E+15 sej/ha/year, respectively, for the rice and wheat production system (Table 3). Thus, the rainfall input was calculated as the total natural renewable resources (energy of rainfall, wind, and sunlight) into the production systems. For rice production in this area, irrigation water was taken as the sole component for the local non-renewable resource flow, which was 3750 m³/ha/year equivalent to an energy value of 1.58 × 10¹⁴ sej/ha (Table 3). Moreover, purchased resources was of 6.50E+15–7.16E+15 sej/ha in the unamended system and of 4.61E+15–7.05E+15 sej/ha in the biochar-amended system (Table 3). These purchased resource contributed to 72–85.9 and 64.6–85.6% to the total energy input, respectively, for unamended and amended system. Of the purchased resource energy input, chemical fertilizer was of 5.38E+15–6.05E+15 sej/ha in unamended system and 3.62E+15–6.05E+15 sej/ha in the biochar-amended system, both being the biggest energy input into the rice-wheat system (50–75% to the total energy input of the whole rotation). Being the second largest purchased energy flow, fuel was in the range of 2.85E+14–3.01E+14 sej/ha in unamended system and 2.58E+14 sej/ha in the biochar-amended system, though only 3% of energy support to the grain production. For a similar contribution, energy input with seed used was 2.49E+14 sej/ha for the whole rotation and was consistent between the biochar-amended system and unamended system. Further, it is worth mentioning that purchased energy was dominated by nitrogen (accounting for almost 45% in total) in both systems. The great quantity of energy received by this flow was

because of the amount of nitrogen used (600 kg/m²/year in unamended and 476–590 kg/m²/year in biochar-amended one) and the large transformativity of this resource.

The calculated emergy indices showed contrasting differences between the two grain production systems with regard to UEV, EYR, ELR, and ESI (Table 4). The UEV for rice ranged from 2.84E+04 to 3.99E+04 sej/J in biochar-amended system and from 3.83E+04 to 4.48E+04 sej/J in unamended one. Comparatively, the UEV for wheat ranged from 2.37E+04 to 3.80E+04 sej/J in biochar-amended system but from 4.44E+04 to 5.05E+04 sej/J in unamended system. Clearly, UEV was lower by 11–47% in biochar-amended system than in unamended system.

However, either slight (under 5%) or no difference was noted in the values of ELR, EYR, and ESI between the biochar-amended and unamended system in the first 2 years (2010–2011) following a single biochar amendment. Nevertheless, for the subsequent years (2012 to 2015), ELR values were lower by 24 and 36% but EYR was higher by 6–9 and 12–16%, respectively, for rice and wheat, in the biochar-amended system than in unamended system. In alignment, ESI was 0.35–0.60 for rice and 0.74–1.07 for wheat in biochar-amended system, compared to 0.25–0.43 and 0.42–0.59, respectively, in unamended one. It is clear that ESI was 40–81% higher in biochar-amended production system than in unamended system, indicating that biochar-amended production system was more economically and ecologically compatible compared to unamended system.

Energy balance

For farm production of the rice-wheat rotation system, energy input was primarily through nitrogen fertilizer (38%) followed by irrigation water (5–7%) and seed used (5–6%; Fig. 2a).

Consumption of energy for other field operations was little or negligible. For rice production, the total energy consumed across the various farm operations ranged from 39,461 to 41,314 MJ/ha in unamended system and from 35,751 to 40,464 MJ/ha in amended one (Fig. 2b). Compared to those for unamended rice, total energy inputs in biochar-amended system were lower compared to those in unamended system, by 2 and 3% in the first 2 years and by about 10% in the subsequent years throughout the field experiment duration. Moreover, for wheat production, the total energy inputs varied in the range of 32,916–33,151 MJ/ha in unamended system but of 22,012–33,012 MJ/ha in biochar-amended system (Fig. 2c). Thus, biochar amendment played a very significant role in reducing energy input to the double crop rotation of rice and wheat, being more dramatically with wheat production.

As shown in Table 5, energy use efficiency (energy ratio) for rice and wheat was calculated to be 6.22–6.95 and 5.28–6.11, respectively, in the unamended system, compared to 7.01–8.43 and 6.16–12.39 in biochar-amended one. For rice production, energy productivity ranged from 0.18 to 0.20 kg/MJ in the unamended system and 0.21 to 0.25 kg/MJ in the biochar-amended system. Again, energy productivity of wheat production ranged from 0.13 to 0.15 kg/MJ in the unamended system and 0.15 to 0.30 kg/MJ in the biochar-amended system. On average, 0.23 kg of rice or 0.24 kg of wheat was obtained per unit energy (MJ) in the biochar-amended system while 0.19 kg of rice or 0.14 kg of wheat in the unamended system. On average of the years, the biochar-amended system resulted in an increase in grain production of 0.04 kg of rice and 0.10 kg of wheat per unit of energy input, over the unamended system. Similarly, the net energy gain was 23% (472,165.87 MJ/ha) higher whereas specific energy (4.40 MJ/kg) was 26% lower in biochar-amended system than in the unamended system (383,019.84 MJ/ha for net energy and 5.93 MJ/kg for specific energy).

Table 4 Emergy indices of the crop systems over the years since biochar amendment

Year	Crop season	UEV (sej/J)		EYR		ELR		ESI	
		NB	BA	NB	BA	NB	BA	NB	BA
2010	Rice	4.39E+04	3.93E+04	1.21	1.21	6.07	5.92	0.20	0.20
	Wheat	4.44E+04	3.80E+04	1.10	1.10	10.25	10.25	0.11	0.11
2011	Rice	4.48E+04	3.99E+04	1.42	1.43	2.78	2.67	0.51	0.54
	Wheat	4.64E+04	3.58E+04	1.29	1.29	3.48	3.48	0.37	0.37
2012	Rice	3.90E+04	2.89E+04	1.25	1.33	4.95	3.80	0.25	0.35
	Wheat	4.63E+04	2.51E+04	1.32	1.49	3.16	2.03	0.42	0.74
2013	Rice	3.83E+04	2.84E+04	1.31	1.41	3.87	2.97	0.34	0.48
	Wheat	4.46E+04	2.37E+04	1.28	1.43	3.63	2.33	0.35	0.61
2014	Rice	4.38E+04	3.15E+04	1.35	1.46	3.42	2.60	0.39	0.56
	Wheat	4.85E+04	2.74E+04	1.36	1.56	2.77	1.77	0.49	0.88
2015	Rice	4.15E+04	3.18E+04	1.37	1.49	3.20	2.46	0.43	0.60
	Wheat	5.05E+04	3.20E+04	1.42	1.65	2.39	1.54	0.59	1.07

NB no biochar amendment, BA biochar amendment

Fig. 2 Composition of energy inputs to rice (a) and wheat (b) and whole rotation (c) production in across years of the experiment

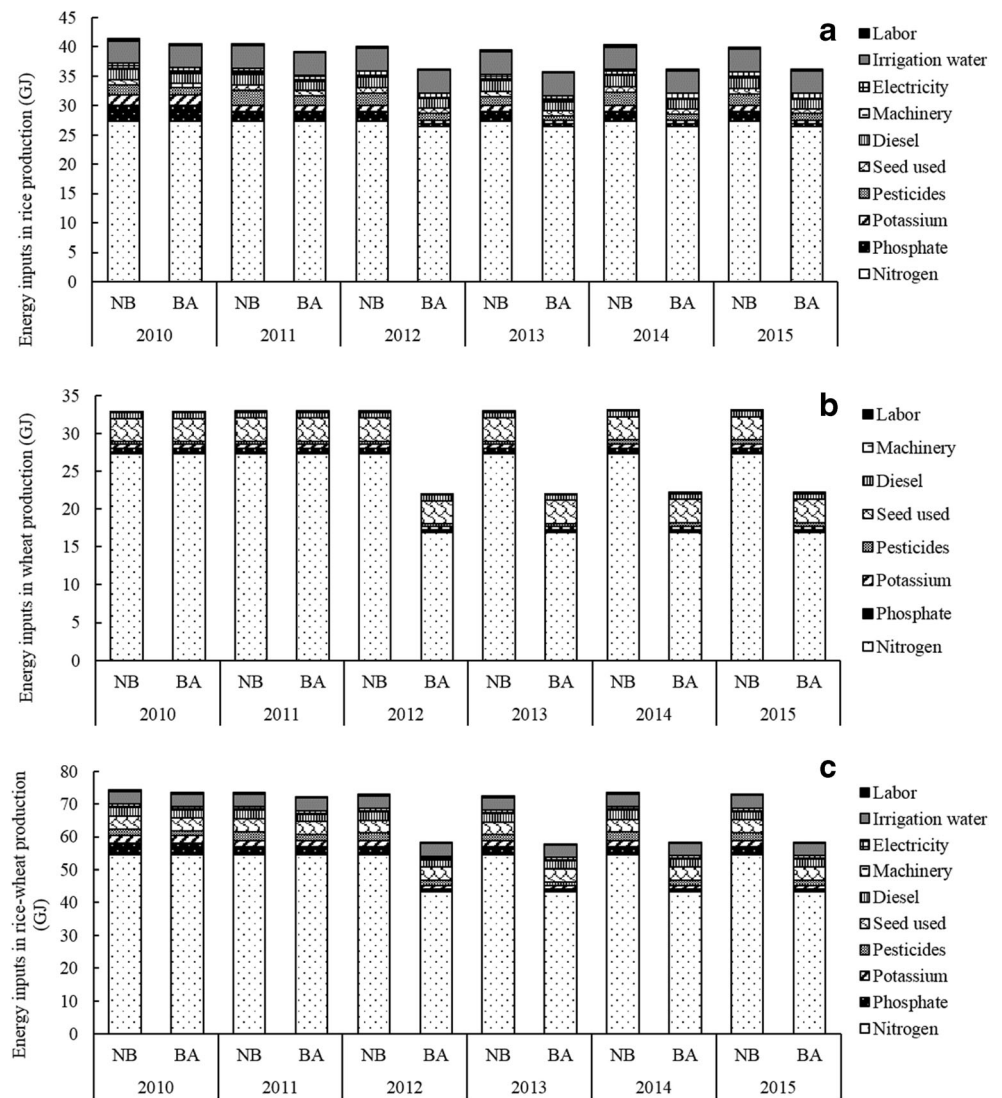


Table 5 Energy balance of the production over the whole experiment course

Year	Crop season	Energy use efficiency		Specific energy		Energy productivity		Net energy (GJ)	
		NB	BA	NB	BA	NB	BA	NB	BA
2010	Rice	6.28	7.01	5.44	4.88	0.18	0.21	218.26	243.01
	Wheat	5.28	6.16	7.84	6.72	0.13	0.15	140.90	169.87
2011	Rice	6.39	7.20	5.34	4.74	0.19	0.21	218.09	242.63
	Wheat	5.92	7.67	6.99	5.39	0.14	0.19	162.33	220.27
2012	Rice	6.51	7.81	5.25	4.37	0.19	0.23	220.25	246.59
	Wheat	6.07	12.22	6.81	3.39	0.15	0.30	167.32	247.00
2013	Rice	6.95	8.43	4.91	4.05	0.20	0.25	234.80	265.49
	Wheat	6.11	12.39	6.78	3.34	0.15	0.30	168.54	251.11
2014	Rice	6.22	7.86	5.49	4.34	0.18	0.23	210.08	247.72
	Wheat	5.99	11.66	6.91	3.55	0.14	0.28	165.50	236.48
2015	Rice	6.68	7.92	5.11	4.31	0.20	0.23	226.51	250.09
	Wheat	5.99	10.60	6.91	3.91	0.14	0.26	165.50	212.81

NB no biochar amendment, BA biochar amendment

Net economic return and cost-benefits

The cost of the inputs used in the production of crop and the gross value of the two production systems are shown in Fig. 3. Calculated according to the market value, the gross production value of rice in the amended production was 7.4–9.8% higher than that in unamended one. Meanwhile, the gross production value of wheat production in the amended system was 18.3–35.5% higher than in the unamended one.

Finally, the benefit-cost ratio for rice production ranged from 1.79 to 2.23 and 2.65 to 3.64 \$ per unit of USD cost, respectively, in unamended and biochar-amended system. Comparatively, the benefit-cost ratio for wheat production ranged from 1.96 to 2.25 and from 2.29 to 3.56 \$ per 1 \$ of money was achieved, respectively, in the unamended and biochar-amended system. Clearly, biochar amendment resulted in an increase in net economical return by 41.3 to 77.8% for rice production and by 34 to 77.2% for wheat production across years following a single amendment in 2009 (Fig. 3b).

Discussion

Significance of N fertilizer inputs and its emergy contribution

China had been the largest user of fertilizer N in the world and facing a daunting challenge of N pollution from excessive

fertilizer use (Ju and Tilman 2009). N fertilizer use efficiency for major cereal crops in China was as low as 30–35% in the 1990s and 25–28% in early 2010s as addressed in field experiments over the country (Zhang et al. 2007). Compared to a high N use efficiency of 68% in Europe and 52% in America (Ladha et al. 2005), the large excess use of N should be greatly reduced without yield penalties, to control potential N pollution to environment in China’s agriculture (Ju and Tilman 2009).

In this study, N fertilizer use was over 300 kg/ha for each crop season of the conventional production. Here, N fertilizer input constituted 35.5–40.6 and 46.2–63% of the total emergy input, respectively, for rice and wheat production in the rotation system. Nitrogen and phosphorous fertilizer together contributed by over 70% to the purchased inputs of emergy for the conventional rice-wheat rotation production from Southwest China (Huang et al. 2015). Characterized with carbon footprint, N dominated (by over 65%) carbon emissions of agricultural production (Yan et al. 2015). For a wheat production from Denmark, N fertilizer contribution by 58% to the total emergy input (Ghaley and Porter 2013). The change in the emergy associated with nitrogen fertilizer demonstrated a high degree of sensitivity to the fertilizer use and transformity for all analyzed systems (Table 6).

Overall, for the grain production systems in this study, N fertilizer used was the primary factor of purchased input influencing the ESI of the system. It had been well demonstrated that high levels of soil organic carbon accumulation

Fig. 3 Production cost (a) and net economic return (b) in biochar (BA)-amended and no biochar (NB) systems across years following a biochar amendment in 2009

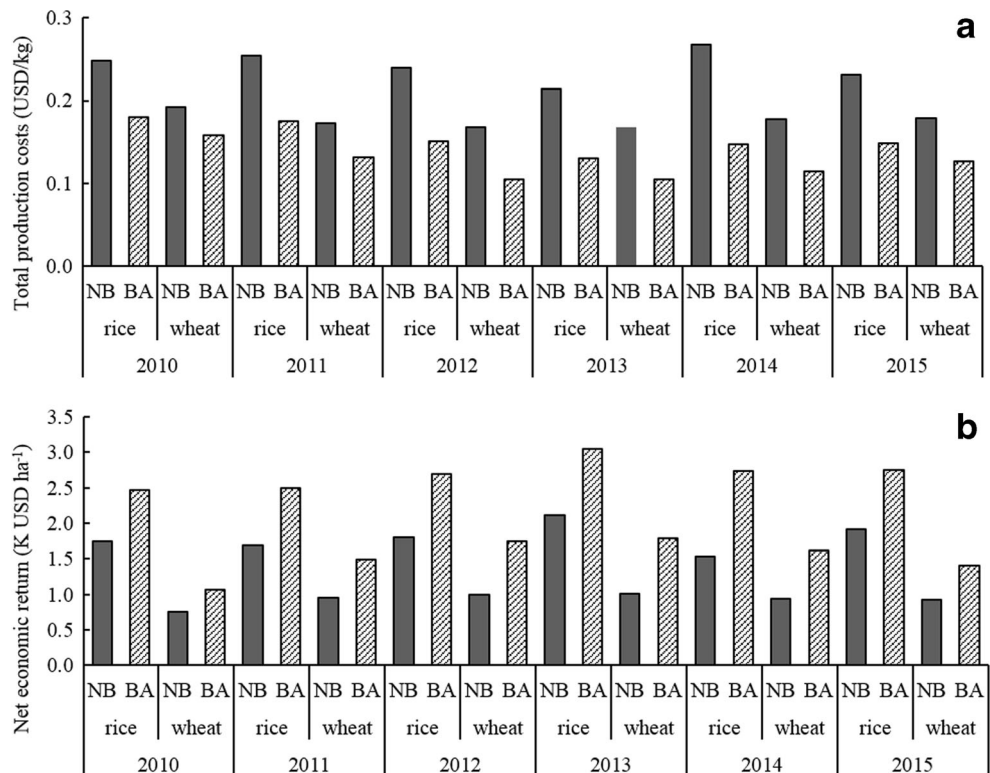


Table 6 The sensitivity analysis of EYR, ELR, and ESI under double and half emergy inputs of the crop system in the study

Index	Emergy input	Rice season			Wheat season			Whole rotation system		
		Rf	Nf	Pf	Rf	Nf	Pf	Rl	Nf	Pf
EYR	Double	21.16	/	/	-40.93	/	/	21.13	/	/
	Half	-10.12	/	/	-11.12	12.19	/	-11.11	/	/
ELR	Double	-50.00	47.46	22.41	-61.52	68.95	14.18	-50.05	56.06	18.93
	Half	99.99	-23.74	-11.21	100.06	-34.43	/	99.80	-28.18	/
ESI	Double	145.06	-36.65	-20.88	52.81	-46.40	-15.05	142.43	-41.62	-19.44
	Half	-54.55	43.44	17.85	-55.77	70.34	/	-55.52	51.79	12.99

Only changes greater than or less than 10% of these ratios and index are noted. Slash indicates less than 10% change

Rf rainfall, Nf N fertilizer input, Pf P fertilizer input

could enhance N efficiency and increase rice productivity as shown in a long-term monitored rice paddy located in the area (Zhang et al. 2010), and biochar amendments could significantly increase N availability to crops (Liu et al. 2012). In addition to avoiding biomass burning but recycling for organic matter amendment to soil, biochar from the straw carbonization would offer a reliable measure to save N fertilizer (Zhang et al. 2010; Huang et al. 2013). Over the unamended system, the N fertilizer used was decreased, by 38 and by 3%, respectively, for wheat crop and rice crop in biochar-amended paddy, during 2012 to 2015 following a single application of 20 t/ha in 2009. As farmers did not claimed a negative yield response to the reduced N use in the biochar-amended paddy, calculation with reduced N fertilizer use but similar amounts of other purchased inputs allowed an emergy evaluation for addressing biochars' role in crop production sustainability of the rice and wheat rotation system. During 2012–2015, 3–6 years following a single application, the mean value of UEV was of $3.35\text{E}+04$ sej/J with an ESI index of 0.48, in the amended system. Whereas, a higher mean UEV value of $4.33\text{E}+04$ sej/J but a lower ESI index of 0.40 was found for the unamended system. Accordingly, the increase in the emergy efficiency by 23% and ESI value by 20% indicated a much improved resource use efficiency with biochar amendment. In a comparative study of emergy analysis using statistical data between Jiangsu and Shaanxi of China, a mean value of 0.50 was estimated for the rice and wheat production of the province of Jiangsu in 2000 (Liu and Chen 2007). Nevertheless, an ESI as low as 0.35 was reported for a conventional wheat-rice rotation system under straw amendments from Southwest China (Huang et al. 2015). Therefore, biochar amendment helped to increase the production sustainability by improving N use efficiency and reducing N fertilizer use, a critical demand for China's agriculture in climate change mitigation (Yan et al. 2015). Biochar soil amendment could be a potential countermeasure, other than those recommended agricultural practices to cut down the ecological footprints of N overuse in China (Ju and Tilman 2009).

Emergy characterization difference between biochar-amended and unamended system

Normally in emergy analysis, the UEV characterized the cost of resources or energy flow for a production for concerns of environmental and economic competition over time (Brown and Ulgiati 2004). In this study, UEV was much lower in biochar-amended system than in the unamended system (Table 4). The reported UEV values of grain production ranged from $3.28\text{E}+04$ to $1.39\text{E}+05$ sej/J (Ghaley and Porter 2013; Li and Yan 2012; Lu et al. 2010; Zhang et al. 2005). In this study, the UEV values of the unamended system fell into this range but those of the biochar-amended system were relatively low, beyond the above range. Particularly, for the period of 2012–2015, the 3–6 years following a biochar amendment, the UEV values of rice were lower than those of grain production mentioned above. While UEV denoted the conversion efficiency of energy with the sources other than local renewable, the lower UEV values of rice season indicated higher energy efficiency under biochar amendment in rice agriculture. Accordingly, rice production, in particular, could become more or less efficient in processing either renewable or non-renewable resources. This could be mutually supported by the consistent yield increase in rice biochar experiments (Huang et al. 2013).

Renewability, as the percentage of local renewable fraction, denoted the contribution of renewable resources to crop production. Calculated renewability (R in % to Y ; Table 3), was significantly higher by over 20% for rice and by over 33% for wheat during 2012–2015 in the biochar-amended system than in unamended one in this study. This indicated a higher portion of renewable resources was involved in crop production in biochar-amended system than in unamended system. Interestingly, this improvement of renewability was relatively high for wheat as a dry crop. This could be related to soil moisture from use of rain resource. As Omondi et al. (2016) presented in a meta-analysis of biochar soil effects, soil moisture could be increased by over 25% in biochar-amended

agricultural soils. Moreover, biochar amendment could supplement nutrients recycled from carbonized crop residue in biochar, significantly of silicon and potassium (Liu et al. 2014b). Such effects could lead to a reduction of purchased resources, which had been well demonstrated in field studies under biochar amendment (Biederman and Harpole 2013; Liu et al. 2013).

Similar findings were observed for other parameters used in energy analysis for the studied systems. Liu and Chen (2007) reported an averaged EYR value of 1.34 and of 1.18 for grain crop production of Jiangsu Province in 1980s and 2000s, being clearly much lower than the estimates in this study. A 0.07 and 0.13 increase in EYR was found, respectively, for rice and wheat in the amended system compared to unamended one over the whole experiment period. The higher increase for wheat relative to rice, particularly over 2012–2015, supported benefits from biochar in dry croplands mentioned above. In a meta-analysis using reported experiments with crops, yield increase under biochar was higher for maize and wheat than for rice (Liu et al. 2013).

ELR values could be indicative of environmental impacts by a production. For a production system, relatively low environment loading could be represented by an ELR close to 2, a moderate impact by a value in range of 3–10, and a very concentrated environmental impact by a value over 10 (Brown and Ulgiati 2004). Using national statistical data, Chen et al. (2006) reported an ELR estimate of 1.74, 2.38, and 2.85 for China's agriculture, respectively, in 1980, 1990, and 1995. Apparently, ELR value estimated hereby for the whole rice-wheat rotation during 2012–2015 was 3.42 on average in unamended system, indicating a moderate environmental impact already. In contrast, the ELR value of estimated for biochar-amended system was seen as small as 2.45 on average. This highlighted the role of biochar amendment in improving ecological integrity for sustainable production of cereals and energy in the long run (Diemont et al. 2006; Ghaley and Porter 2013). This could be attributed to a number of environmental benefits from biochar including increasing organic carbon stability (Lehmann and Joseph 2015), mitigating greenhouse gas emission including N₂O emission (Cayuela et al. 2013), improving soil aggregation and infiltration (Omondi et al. 2016), metal immobilization (Park et al. 2011), and nutrient salt leaching loss (Xu et al. 2016). The effects on soil respiration from organic carbon mineralization (Liu et al. 2016), soil greenhouse gas emission (Zhang et al. 2010, 2012a), on toxic metal immobilization (Bian et al. 2013, 2014), and improved microbial growth (Chen et al. 2013, 2015), had been well demonstrated under field monitoring in this site and beyond.

As a key indicator of ecological and economic sustainability of a production process (Diemont et al. 2006; Ghaley and Porter 2013), ESI value was estimated as 0.37 on average in

unamended system compared to 0.51 on average in biochar-amended system. In 2010, the first year following an application, ESI value was estimated as low as 0.20 for rice and 0.11 for wheat both in unamended and amended system. While ESI values were considerably variable in unamended system, there was an overall increasing trend over the years following the biochar application (Table 4). The consistent increase in ESI value in biochar-amended system, approaching 1.0 particularly for wheat production, indicated an improvement of system performance with minimum environment pressure (Brown and Ulgiati 2004). The work by Liu and Chen (2007) using statistical data gave an ESI value of 0.50 for the grain production from Jiangsu Province in 2000s. The higher but increasing ESI values in biochar-amended system observed in this study highlighted again a sustainable biochar effects beneficial for crop production, as addressed previously by Liu et al. (2014a). The improved system performance for crop production could be associated with a system acquainted resistance (SAR) with biochar (Graber et al. 2014), which had been raised as a cut-edging paradigm for biochar technology in agriculture and global sustainable soil management.

Economic potential of biochar

Household farmers often had other jobs for primary income in the nearby towns despite of farming subsidies available from the government (Gale et al. 2006). Most of the crop production systems in China had been operated in household small-scale farms (Zhang et al. 2013b). Most of the cost for crop production was from purchase and use of fertilizers and pesticides. However, chemical fertilizers and pesticides, used to apply in large amount but minimum times, exert significant negative impacts on soil, water, and human health (Huang et al. 2000). In this study, N saving and less pesticide use of direct cost for the purchased inputs was achieved with biochar amendment. Meanwhile, labor cost could be reduced with less spraying of fertilizers and pesticides on farm. In addition, cost was less in biochar-amended rice system when a collapse occurred after a storm event. During the farm survey, farmers often argued on increased working time for mechanical operation in harvesting, which costed normally about 200 USD per hectare. Overall, an apparent economic gain was achieved for a whole rice and wheat rotation around 1.5×10^3 USD per hectare in the biochar-amended system (Fig. 3), when biochar cost was not a concern.

With regard of UEV values, wheat production was lower in energy efficiency than rice in the unamended system but the reverse is true in biochar-amended system (Table 4). A meta-analysis also showed that biochar-induced yield gain was greater with upland crops than irrigated paddy rice (Liu et al. 2013). Thus, a higher yield gain could be expected with wheat with the same energy. However, according to the prices in Chinese food market (DP-NDRC 2016), an economic gain

was greater for rice (899 USD per hectare on average) than for wheat (600 USD per hectare on average) in the biochar-amended system. Herein, there could be a tradeoff between improvement of grain production and increased in economic gain in the crop production with biochar amendment. Such situation would cause a dilemma for policy makers and farmers to adopt biochar in croplands of paddy rice versus dry crops.

In this study, biochar used for amendment was pyrolyzed from wheat straw. The biochar amendment at a rate of 20 t/ha would cause a cost of 4000 USD per hectare. Averaged on the 6 years following a single application, this cost was relevant to about 600 USD per hectare, corresponding to the economic gain of wheat production per year. Indeed, the agro-benefits and economic gain reported here could be marginal for biochar use for cropland amendment, which was concerned not competitive in absence of a carbon trading mechanism for agriculture (Clare et al. 2014).

Direct straw return had been conventionally incentivized in China to avoid air pollution while to recycle nutrients back to cropland. Generally, farmers should pay back 96 USD per hectare for wheat straw or 192–240 USD per hectare for rice straw pulverization plus additional 72 USD per hectare for increased pesticide spraying each crop season (Li et al. 2013). In courtesy, biochar production from straw carbonization and use for soil amendment and fertilizer improvement had been approved to develop into large-scale commercialization (General Office, Ministry of Agriculture of China 2017). Taking advantage of an ongoing carbon reduction marketing in China, biochar use for soil amendment in production systems like in this study could become economically viable. And such change would help China's agriculture to sustain crop production while to cut down not only carbon emission but also environmental loading.

Conclusions

This study quantified energy balance for rice and wheat rotation system between biochar-amended and non-amended system throughout 6 years following a single application in a rice paddy from China. Our estimates suggest that biochar had a substantial and persistent ecological and economic benefits, which could be more prominent for wheat than for rice. Despite this, there was a tradeoff in grain yield and economic gain between rice and wheat. At courtesy of ongoing national projects of carbon trading and straw recycling policy, production of biochar from crop straw and use for cropland amendment could become economically viable. The upscaling of biochar use could be a measure to boost grain production while minimize environmental impacts from China's agriculture sector.

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