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Impact of fertilization schemes with different ratios of urea to controlled release nitrogen fertilizer on environmental sustainability, nitrogen use efficiency and economic benefit of rice production: A study case from Southwest China

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ABSTRACT

Controlled release nitrogen fertilizers (CRNF) possess good nutrient release performance and application prospects. Under the dual pressures of food security and environmental protection, whether substitution of urea using CRNF could improve environmental sustainability of rice production relative to the utilization of single urea, as well as ensure the rice yield and farmers' income, should be deeply investigated to promote wide application of this kind of fertilizer. Based on one-year field experiment and field surveys, four fertilization schemes with different ratios of urea to CRNF were set up, i.e., control (CK), local recommended application amount urea (N1), 100% CRNF (N2), and the combined application of 60% CRNF and 40% urea (N3). Adjusted emergy accounting (EMA), which considers emissions' impacts, and nitrogen use efficiency (NUE) as well as economic indicators were applied to the comparison of environmental sustainability, agronomic indicator and economic benefit of different schemes respectively. The results showed that (1) CRNF utilization raises environment sustainability by 2.82–4.61%; (2) CRNF utilization improves nitrogen use efficiency by 30.65–43.96%; (3) CRNF utilization enhances economic benefit by 5.21–11.44%. Generally, N3 has the best system coordination degree among the three fertilization schemes. Finally, the study suggested popularizing the scheme N3 in this region through adopting appropriate financial and policy support. Meantime, technological innovation, and regulatory supports are needed to accelerate the development of the CRNF industry.

1. Introduction

Controlled release nitrogen fertilizer (CRNF) is superior to urea due to improving nitrogen efficiency, increasing yield, and saving manpower and material resources (Naz and Sulaiman, 2016; Zheng et al., 2016). From 2010 to 2016, production and sales volume of controlled-release fertilizers exceeded 21 million tons and were widely used in crop production of wheat, maize, and rice, with a cumulative area of approximately 35,000,000 ha in China (China Industry Technology Innovation Strategic Alliance et al., 2016). By the end of 2016, 36 products, such as sulfur-coated fertilizer, resin-coated fertilizer, and chemical inhibition fertilizer etc., have received the registration certificate of slow/controlled release of fertilizers in China within the valid period (Zhou et al., 2017). Besides, the International Fertilizer Association (IFA) reported that CRNFs will continue to show rapid growth in the next few years due to their good prospects. Application of CRNFs can enhance nitrogen utilization efficiency and then cut nitrogen loss in the environment. However, as artificial chemical fertilizers, CRNFs need additional inputs of resources, energy sources, and labor service in their

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production process, which also causes extra impacts on economic benefit of crop production and local environment. Therefore, evaluating comprehensive performance of CRNFs application in crop production could better promote popularization of this kind of fertilizers in crop production as well as development of this fertilizer industry in the future.

Researchers have adopted multiple system methods to evaluate performance of crop production. For instance, Yang et al. (2019) investigated comprehensive performance of a cropping system using life cycle assessment (LCA), emergy accounting (EMA), and economic analysis (EA); Xu et al. (2019) carried out an EMA and EA of a rice-crab symbiotic system; EMA, energy flow analysis (EFA) and EA were jointly adopted to assess performance of crop production (Wang et al., 2018); an EMA was implemented to explore performance of maize production (Moonilall et al., 2020); EMA and fuzzy logic analysis were done to investigate performance of a rice production system (Amini et al., 2020), etc. Considering different characteristics of diverse evaluation methods (Table 1), researchers prefer to adopt joint use of more than two methods to overcome the limitations of single one, so as to achieve comprehensive assessment of systems being analyzed. Comparatively speaking, EMA has become one of policy-making tools of agricultural production due to its consideration of the environmental contribution and quality differences of diverse inputs (Zeng et al., 2013), as well as its strong inclusivity in environmental assessment and policy suggestions (Tennenbaum, 2015).

Agricultural system is often affected by both climate change and the local ecological environment. Therefore, scholars attempted to adjust the components of input or indices in EMA according to local specific characteristics to achieve targeted evaluation. Lu et al. (2010) considered dynamic changes of soil organic matter into sustainability evaluation of rice and vegetable production systems in alluvial paddy fields. In circular agriculture systems, calculation method for organic matter consumption was improved, and use of waste and local renewable resources was integrated into the emergy yield ratio (Wang et al., 2017). Agricultural pollutants' impacts were included in EMA of three different types of agricultural production systems in China (Su et al., 2020). Amini et al. (2020) put forward a regional model based on EMA. The improved methods and policy suggestions are put forward in the existing studies, based on the traditional emergy indicators, such as the renewable fraction (R%), emergy yield ratio (EYR), environmental loading ratio (ELR), emergy sustainability index (ESI) etc. However, the following issues have not been well addressed in the existing studies, including quantification of all kinds of environmental effects of rice production (such as groundwater recharge, carbon sequestration, oxygen release etc.; Lee et al., 2015), and clarification of net environmental impact or net ecological benefit of rice production.

Nowadays, a considerable amount of literature has been published on the application of CRNF in agricultural systems. And most of existing studies concentrated on comparisons of nitrogen loss and efficiency (Xiao et al., 2019), environmental impacts (Ke et al., 2018), agronomic effects (Deeks et al., 2013), accurate application rate and methods (Guo et al., 2017) between CRNF and conventional urea. Generally these studies considered single variables that could bring contribution or damage to a system, and thus could attain biased results due to uncompleted information. Further, they ignored the natural contribution to agricultural system. Particularly, there is still a research gap in the EMA of crop production for comparing environmental sustainability of different nitrogen fertilization schemes with different ratios of CRNF to urea through considering ecological benefit and environmental impacts of crop production simultaneously.

In recent years, the Chinese government has attached great importance to the development of the CRNF industry. The promotion of CRNF was mentioned many times in "No. 1 Central Document", "Five-Year Plan", and the national medium and long-term science and technology development plan. However, in Southwest China, CRNF has not been widely applied. Whether the application of CRNF or part substitution of urea has advantages over single urea utilization in purple soil area, according to environmental, agronomic and economic indicators, is worthy of further exploration for promoting application of CRNF. In this study, a one-year field experiment and local investigation were conducted in Yanting county, Mianyang city, Sichuan Province, Southwest China, EMA was firstly applied to environmental performance evaluation of the four rice production schemes with different ratio of CRNF to urea, i.e., control, with no fertilization (CK), local recommended application amount urea (N1), 100% CRNF (N2), and combined application of 60% CRNF and 40% urea (N3). Then nitrogen efficiency was compared to depict the agronomic benefit of three schemes, followed by the implementation of brief economic evaluation to compare the economic performance of four schemes. Next, one compound index, i.e., system coordination degree (SCD), which integrates environmental, agronomic, and economic indicators, was founded to assess the comprehensive performance of rice production. Finally, appropriate suggestions were proposed. This study can contribute to the related fields through (1) improving emergy evaluation of rice production through considering beneficial ecological service and adverse emissions' impacts and then founding one set of adjusted indicator system; (2) promoting integrated assessment of rice production through using the proposed SCD linking the environmental sustainability with nitrogen use efficiency and economic performance; (3) enriching the existing

Table 1
Comparison of different evaluation methods.

Methods	Main content	Limitations
Life cycle assessment (LCA)	LCA assesses the input, output, and potential environmental impact of a product system in its life cycle (ISO, 2006a, b).	LCA stops at the resource level and evaluates the upstream impact while contribution of natural inputs (e.g., sunlight, rainfall) are not considered (Raugei et al., 2014), and it does not distinguish quality differences of all kinds of inputs.
Economic analysis (EA)	It measures economic value of goods, labor and service in terms of currency value in social economy and concentrates on human contribution.	The rapid change of market supply and demand, coupled with the subjectivity of human cognition, makes the results of EA somewhat subjective and limited (Zhang et al., 2018a); meanwhile, it ignores or distorts environmental contribution.
Energy flow analysis (EFA)	It calculates the energy input-output ratio of the system and the efficiency of energy conversion from one form to another.	Only the energy flow and transformation are considered and it ignores the contribution of natural inputs and differences of diverse energy sources (Zhang et al., 2018a)
Emergy accounting (EMA)	It considers environmental and human contributions to social economic systems, and measures all kinds of inputs' contributions in terms of united unit (solar energy joule, sej) (Odum, 1996).	Unit emergy values (UEVs) are closely related to the space and time scales of the biosphere and thus they may sometimes be characterized with uncertainty (Brown et al., 2012). Meanwhile, real economic benefit and environmental emissions' impacts have not been well reflected in classic EMA yet.

database of unit emergy values using updated unit emergy values (UEV) of rice products.

2. Materials and methods

2.1. Site description, experimental design, and sampling

2.1.1. Site description

The field experiment was conducted in Yanting County (105°12′17″~105°43′20″E, 30°58′31″~31°29′40″N), located in the central Sichuan Basin, Mianyang City, Sichuan Province, Southwest China. The landform is dominated by low mountains and hills, with an altitude of 400–600 m. It has a typical subtropical humid monsoon climate. The average annual air temperature is 17.3 °C, the extreme maximum temperature is 40 °C, and the extreme minimum temperature is −5.1 °C. Annual average precipitation is 836 mm and the average wind speed is 2.6 m s^{-1}. The soil is mainly composed of calcareous purple soil and paddy soil, accounting for 72.8% and 23.26% of the cultivated land area of the county. The recommended fertilization scheme for rice production (N1) in the study area is 150 kg N ha^{-1}, 75 kg P_2O_5 ha^{-1}, 75 kg K_2O ha^{-1} respectively.

2.1.2. Field experimental schemes

The experimental treatments and related plot design were shown in Table 2 and Fig. 1, respectively. The CRNF used in the study was polyurethane coated CRNF with nitrogen content of 44% and a release period of 90 days, and it was provided by Institute of Agricultural Resources and Regional Planning in Chinese Academy of Agricultural Sciences. Urea was purchased from a local market with a nitrogen content of 46% (Sichuan Meiqing Chemical Co., Ltd., China). The nutrient contents of phosphate fertilizer and potassium fertilizer are 12% of P_2O_5 and 60% of K_2O, respectively. The adopted rice variety was Yixiang 725, rice cultivation was finished on May 7, 2018, and harvested on August 28, 2018. Experimental treatments for the study were laid out according to a randomized completed block design, and four treatments were considered, including CK, N1, N2, and N3. Therein, the urea topdressing stage was one week after transplanting of rice seedling. Except for the CK, the other three treatments applied the same amount of total nitrogen, total phosphate, and total potassium. The area of each plot is 21 m^2, with a length of 7 m and a width of 3 m. Independent water inlet and water outlet were designed in each plot. Each treatment included four replications, and then there were 16 experimental plots. Each plot was separated from other ones by 50 cm high ridges which were covered with plastic film to prevent leakage. When transplanting rice seedling, the rice plant spacing was 20 cm and the row spacing was 40 cm. Each plot was irrigated before rice transplanting, and the field management method was the same as the local management way.

2.1.3. Sampling and measurement

(1) Soil. Firstly, the topsoil (0–10 cm) was collected before rice transplanting and after harvesting the rice grain for the determination of soil organic matter. And then the soil organic matter content was measured using $K_2Cr_2O_7$–H_2SO_4 oxidation at 180–185 °C in an oil bath (Bao, 2000).

(2) Plant. The yield was determined by sampling the rice plants from 2 m^2 in each plot at the maturity period. Unhulled (rough) rice kernels were obtained after reaping, threshing, and winnowing. The weight of the rough rice kernels was adjusted to a moisture content of 13.5%.

(3) Environmental pollutants. Ammonia volatilization was determined by closed chamber intermittent ventilation. CO_2 and CH_4 emissions were monitored by static black box-gas chromatography. Pollutants in groundwater were collected from depth of 60 cm underground (Embed the collection device-clay tube in advance in each plot, with a depth of 60 cm, and collect the water in the 1st, 3rd, 5th, and 7th day after the rain). As different nitrogen fertilization schemes were involved in this study, only nitrogen-related water pollutants were considered. The concentration of NH_4^+-N and NO_3^--N in the water sample was determined by the SEAL Auto Analyzer 3 continuous flow analyzer.

2.2. EMA

Emergy, created by Odum (1996), was defined as the sum of one available energy directly or indirectly used to generate a product or a service. All the inputs are converted into the same measurement unit by their corresponding unit emergy values (UEVs), generally expressed in solar equivalent joules (sej) in EMA. The relevant emergy amounting must be based on the same baseline for keeping consistency. Up to now, the emergy baseline has experienced several revisions due to different calculation methods by various researchers, i.e. 9.44 E+24 sej y^{-1} (Odum, 1996), 15.83 E+24 sej y^{-1} (Odum, 2000), 9.26 E+24 sej y^{-1} (Campbell et al., 2005), 15.20 E+24 sej y^{-1} (Brown and Ulgiati, 2010), and 12.00 E+24 sej y^{-1} (Brown and Ulgiati, 2016). As for rules of emergy 'algebra', each input supported system was computed by multiplying the quantity (energy content or mass or monetary value) by the corresponding UEV, and total emergy input (U) was calculated as follows.

$$U = \sum E_i \times UEV_i \tag{1}$$

where U is the total emergy input (sej), E_i is amount of energy or mass or money of i-th input (J or kg or monetary unit) and UEV_i is UEV of i-th input (sej J^{-1} or sej kg^{-1} or sej per monetary unit), respectively. In this study, all the UEVs being cited were corrected to the baseline 12.00 E+24 sej y^{-1} to keep consistency. In addition, areas of four treatments were adjusted to a unit area of 1 ha in one year to ensure standard comparisons.

2.3. Emergy flows of rice production system

Emergy system language diagrams of the four treatments were shown in Figs. 2 and 3. All the inputs supporting the system include local renewable resources (R), local nonrenewable resources (N), and imported inputs (F). Therein, R was derived from primary flows (sunlight and earth cycle), secondary and tertiary sources (wind, rain, and runoff). In this study, amount of R was chosen as the

Table 2
The amount of fertilizer applied (kg ha^{-1}).

Treatments	CRNF (N 44%)	Urea (N 46%)	P_2O_5 (P_2O_5 12%)	K_2O (K_2O 60%)	Urea topdressing (N 46%)
CK	0	0	0	0	0
N1	0	196	625	125	130
N2	341	0	625	125	0
N3	205	130	625	125	0

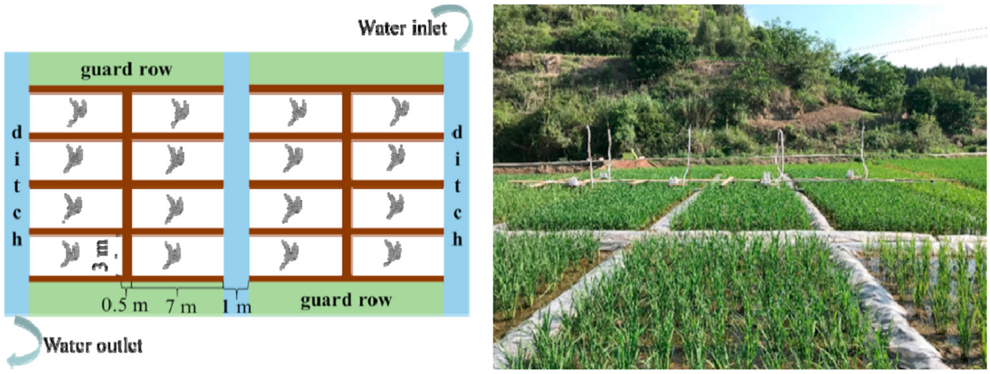

Fig. 1. Experiments' design of this study.

largest one among primary flows, secondary and tertiary resources in order to avoid double counting (Brown and Ulgiati, 2016). N refers to soil erosion. F is comprised of agricultural materials (including diesel, machinery, electricity, seed, fertilizers, pesticides, and labors and services (L&S)). Here F was divided into renewable imported inputs (F_R) and nonrenewable imported inputs (F_N). Detailed calculation of renewable fraction of labors and services (L&S) was shown in Supporting Materials (SM. 1). Rice production systems not only provide rice yield but also provide several kinds of beneficial ecosystem services (BES, such as groundwater recharge, carbon sequestration), which will enhance their potential positive output. Meanwhile, as human-dominated systems, environmental emissions (here mainly including ammonia volatilization (NH_3), CH_4 and CO_2 emissions in the rice production process) and groundwater pollutants (NH_4^+-N, NO_3^--N), will adversely affect the environmental quality and human health, and then lead to a potential economic loss (here named as emergy loss (EL)), which could weaken its positive output. In addition, the extra ecological services' emergy (ESE) from the atmospheric environment is needed to reduce air emissions to an acceptable level through environmental self-purification, and this will lead to additional environmental loading. The following section described methods for quantifying several emissions' impacts.

2.4. Quantifying BES and emissions' impacts

2.4.1. Quantifying BES

Rice production consumes more water than any other crop system while it also recharges groundwater because the paddy field is flooded for a long time. The calculation formula of recharged groundwater is as follows (Shah et al., 2019).

$$Em_{WR} = P \times \rho \times S \times k \times UEV_{GW} \tag{2}$$

where Em_{WR} refers to the emergy of recharged groundwater (sej); P is the precipitation in the study area (m); ρ means the water density (kg m^{-3}); S refers to the cultivation area (m^2); k is the infiltration coefficient of the study area, and it is 0.203 (Liu, 2007); UEV_{GW} is the specific emergy value of groundwater, 4.96E+08 sej kg^{-1} (Brown and Ulgiati, 2020).

On the one hand, rice converts atmospheric carbon dioxide into carbohydrates through photosynthesis and then fixes it in plants and soil in the form of organic carbon. Here we considered the carbon sequestration derived from the increase of biomass as a carbon sink. On the other hand, as a carbon source, carbon emissions exist during rice planting stage. In this study, we considered direct carbon emissions only in the rice planting stage, including the CO_2 and CH_4 emission, carbon emissions from energy-burning

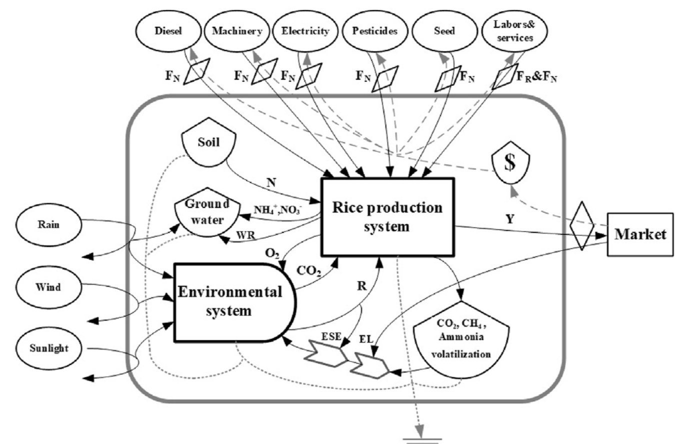

Fig. 2. Emergy system diagram for rice production without fertilizer application (CK). R: local renewable resources; N: local nonrenewable resources; F_R: renewable imported inputs; F_N: nonrenewable imported inputs; Y: emergy of rice yield; EL: emergy loss; ESE: ecological services' emergy; WR: groundwater recharge.

and labors. The net carbon sequestration amount of the rice system is the difference value between carbon sink and carbon source, calculated using Formula (3). In this study, CO_2 equivalent (kg CO_2-eq) is uniformly used as the accounting unit of net carbon

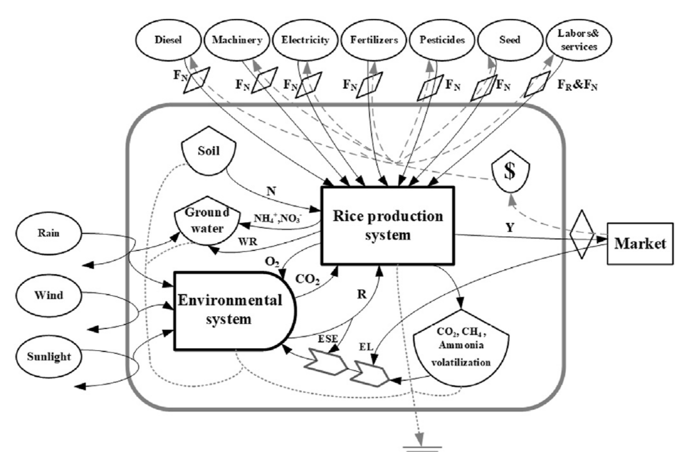

Fig. 3. Emergy system diagram for rice production with fertilizer application (N1, N2, N3). R: local renewable resources; N: local nonrenewable resources; F_R: renewable imported inputs; F_N: nonrenewable imported inputs; Y: emergy of rice yield; EL: emergy loss; ESE: ecological services' emergy; WR: groundwater recharge.

sequestration. All the emission coefficients were shown in SM 2.

$$CS_{NET} = C_{SINK} \times \frac{44}{12} - C_{SOURCE} \quad (3)$$

where CS_{NET} refers to net carbon sequestration (kg CO_2-eq); C_{SINK} is the carbon sequestration derived from the increase of net primary productivity (NPP, kg C), which is approximately equal to 45% of the biomass, including the aboveground and underground biomass (Luo, 2009), $\frac{44}{12}$ is the conversion factor for converting carbon into carbon dioxide; C_{SOURCE} means the carbon emissions during rice production (kg CO_2-eq). A detailed calculation procedure was shown in SM. 2. Here, $CS_{NET}>0$ stands for net carbon sequestration, $CS_{NET}<0$ means net carbon emission and $CS_{NET} = 0$ reflects carbon balance. Therein, net carbon sequestration could bring about ecological benefit through mitigating greenhouse effect, net carbon emission could lead to potential loss due to worsening greenhouse effect, and they can be quantified in terms of emergy. Ecological benefit of net carbon sequestration can be calculated as follows (Shah et al., 2019).

$$Em_{NCS} = CS_{NET} \times UEV_{CS} \quad (4)$$

where Em_{NCS} refers to ecological benefit of net carbon sequestration in terms of emergy (sej); CS_{NET} means the net carbon sequestrated by rice production systems (kg CO_2-eq); UEV_{RICE} refers to the specific emergy value of biomass in rice production (sej·kg^{-1} CO_2-eq), and it can be calculated as follows (Shah et al., 2019).

$$UEV_{CS} = \frac{Em_R}{NPP \times \frac{44}{12}} \quad (5)$$

where UEV_{CS} is the UEV of carbon sequestration of rice production systems (sej·kg^{-1} CO_2-eq); Em_R refers to the renewable emergy for NPP in the rice production systems (sej), which equals to the emergy of local renewable resources (Liu and Yang, 2018). NPP is the NPP of rice (kg C), $\frac{44}{12}$ is the conversion factor for converting carbon into carbon dioxide, according to Ref. (Wang et al., 2016), and detailed calculation procedure was shown in SM. 3. Finally, the emergy of BES is calculated as flows.

$$Em_{BES} = Em_{WR} + Em_{NCS} \quad (6)$$

2.4.2. Quantifying EL

EL, caused by carbon and NH_3 emissions as well as groundwater pollutants discharge, is extensively concerned. In this study, Eco-Indicator 99 assessment method was applied to quantification of initial damage caused by carbon and NH_3 emissions and groundwater pollutants discharged. Human health loss can be measured by DALYs (Disability Adjusted Life Years) (Goedkoop, 1999). Meanwhile, the environmental capacity should also be considered when calculating this loss. When the emissions exceed the environmental capacity, the additional environmental burden will appear. The human health losses are calculated using the following formula:

$$EL = \sum (M_{iS} - EvC_{iS}) \times DALY_i \times T_{Hj} \quad (7)$$

where EL means the emergy of human health loss (sej); M_{iS} refers to mass of the i-th air emission in the air environment or i-th pollutant discharged in the groundwater (kg). Therein, for carbon emission, it equals to the mass of carbon emission in Formula (3); for discharge of NH_4^+-N and NO_3^--N in groundwater, the amount is estimated by using the product of amount of groundwater recharge and related pollutant concentration according to Formula (8); EvC_{iS} is the environmental capacity of i-th air emission or groundwater pollutant in the study area. Due to the lack of data, this parameter is chosen as zero; $DALY_i$ refers to the DALY value caused by the i-th air emission or groundwater pollutant (yr person kg^{-1}); T_{Hj} means the emergy use per capita in 2018, with the number 8.84E+13 sej person^{-1} yr^{-1}, whose detailed calculation procedure was shown in SM. 4.

$$M_{WP} = V_{WR} \times C_{WP} \quad (8)$$

where M_{WP} refers to the mass of i-th groundwater pollutant (kg); V_{WR} is the volume of groundwater recharge (L), obtained through Formula (2); C_{WP} stands for the concentration of i-th pollutant in groundwater (kg L^{-1}), attained through experimental monitoring. In this study, according to the quality standard for groundwater for agricultural and industrial use (III) in China (Ministry of Water Resources of People's Republic of China, 2018), average concentrations of NH_4^+-N and NO_3^--N in all the treatments were lower than related legal limits in the standard during the study period. Therefore, there is no potential damage caused by pollutants discharge in groundwater.

2.4.3. Quantifying ESE

To satisfy the related environmental quality standards, environmental emissions often need extra ecological service to reduce their concentrations to satisfy legal requirements through environmental self-purification function. When environmental emissions are within local environmental capacity, no extra ecological services are needed; on the contrary, extra ecological services are needed and then lead to extra load on the local environment, and this extra ecological service can be calculated as follows. Firstly, the mass of extra air/water to dilute air emissions/groundwater pollutants is calculated by Formula (9).

$$M_{i,air/water} = D_{air/water} \times \frac{\left(M_{i,air/water} - EvC_{i,air/water}\right)}{C_{i,air/water}} \quad (9)$$

where $M_{i,air/water}$ is the mass of extra air or water to dilute the i-th pollutant (kg); $D_{air/water}$ means the air or water density (1.23 kg m^{-3} for air, 1000 kg m^{-3} for water); $M_{i,air/water}$ refers to the mass of i-th air/water pollutant in rice production (kg); $EvC_{i,air/water}$ is the environmental capacity of i-th air/water pollutant in the study region, here it is still considered as zero for air emissions while it is larger than groundwater pollutants discharge according to our experimental data; $C_{air/water}$ is the acceptable concentration of i-th pollutant in local area. Therein, C_{CH_4} and C_{CO_2} are the average concentrations in the atmosphere in 2018, with the value of 3.26E-06 kg m^{-3} (Dlugokencky, 2018) and 5.01E-04 kg m^{-3} (Dlugokencky and Tans, 2018), respectively; C_{NH_3} refers to the standard value of NH_3 (2.00E-04 kg m^{-3}) in the indoor air quality standard of China (Ministry of Ecology and Environment of People's Republic of China, 2002); the acceptable concentrations of NH_4^+-N and NO_3^--N were cited from the quality standard for groundwater for agricultural and industrial use (III) in China (Ministry of Water Resources of People's Republic of China, 2018). Next, ESE can be obtained according to the following equations.

$$ESE_{i,air} = \frac{1}{2} \times M_{i,air} \times V^2 \times Tr_{wind} \quad (10)$$

$$ESE_{i,water} = M_{i,water} \times \rho \times Tr_{water} \quad (11)$$

where $ESE_{i,air}$ refers to the emergy to dilute the i-th air pollutant (sej); $M_{i,air}$ is the mass of extra air to dilute the i-th pollutant emission (kg); V means the wind velocity (here 0.52 m s^{-1}); Tr_{wind} refers to the transformity of wind energy, i.e. the value of 8.00E+02 sej J^{-1} (Brown et al., 2016). $ESE_{i,water}$ refers to the emergy to dilute the i-th groundwater pollutant (sej); $M_{i,water}$ is the mass of extra water to dilute the i-th pollutant (kg); ρ means the thermal value coefficient of water, 1.39E+05 J kg^{-1} (Zhang et al., 2018a); Tr_{water} refers to the transformity of water energy, i.e. 2.13E+04 sej J^{-1} (Brown et al., 2016). Since wind energy or water can dilute diverse air pollutants or groundwater pollutants simultaneously, the total ESE value is equal to sum of the greatest value among $ESE_{i,air}$ and the largest one among $ESE_{i,water}$ to avoid double accounting, as follows.

$$ESE = \max(ESE_{i,air}) + \max(ESE_{i,water}) \quad (12)$$

2.4.4. Net environmental effect

Finally, the net environmental effect of rice production system can be summarized using Formula (13).

$$Em_{NEE} = Em_{BES} - EL - ESE \quad (13)$$

where Em_{NEE} is the emergy of net environmental effect. If the parameter value > 0, that means the rice production system brings about positive environmental benefits. On the contrary, it causes negative environmental effect. And $Em_{NEE} = 0$ means no environmental effect.

2.5. Corresponding emergy-based indicators

Emergy based indicators results reflect resources' structure and how resources input in natural systems and human-dominated systems be allocated, and then can be used to compare the performance of different systems from different angles. Due to extra ecological services and adverse emissions' impacts will potentially influence the environmental sustainability of one system while beneficial ecological service could improve its sustainability, here the following adjusted emergy indicator system was proposed to describe the environmental performance of the four rice production systems, i.e. UEV, R%, adjusted emergy yield ratio (AEYR), adjusted environmental loading ratio (AELR), and adjusted emergy sustainability index (AESI).

(1) UEV: UEV is the ratio of total emergy without L&S input to rice yield (sej kg^{-1}). UEV can evaluate production efficiency. For different processes with same/similar products or service, lower UEV values mean higher production efficiency (Pulselli et al., 2011). It can be obtained through the following formula.

$$\frac{U - Em_{L\&S}}{Y} \quad (14)$$

where U is the total emergy of all inputs (sej); $Em_{L\&S}$ refers to the emergy of L&S (sej); Y means the rice yield (kg).

(2) R%: It is percentage of renewable inputs (including F_R) in the total emergy input of the system. In general, the larger proportion of renewable resources in a system, the more sustainable the system would be in the long run (Pulselli et al., 2011). It is calculated by using the following formula:

$$R\% = \frac{(R + F_R) \times 100\%}{U} \quad (15)$$

(3) AEYR: This is an improved indicator based on the classic indicator EYR, which is defined as the total emergy divided by inputs. EYR can be used to measure the system's ability to utilize resources input, i.e. the higher indicator value means a higher yield emergy per unit of invested emergy. In rice production systems, emergy loss will reduce the net emergy output while beneficial ecological services will enhance the net emergy output. Therefore, we integrated the emergy of beneficial ecological services and emergy loss into the indicator. This indicator represents the ability of a system to explore the local resources while considering its impacts on human health and the environment. The bigger indicator value means a stronger competitive ability, and it can be calculated using the following formula.

$$AEYR = \frac{U + Em_{BES} - EL}{F} \quad (16)$$

(4) AELR: Classic emergy indicator ELR is defined as the sum of local nonrenewable resources and imported inputs divided by local renewable resources. This index measures the potential environmental stress of a system as the ratio of nonrenewable to renewable resources used. In general, the higher indicator value reflects the larger press on the local environment. In this study, we divided imported inputs into renewable and nonrenewable ones, and extra ecological service needed to dilute environmental emissions was also considered. And then the improved indicator-AELR can be attained, as follows.

$$AELR = \frac{N + F_N + ESE}{R + F_R} \quad (17)$$

(5) AESI: Classic ESI reflects the sustainability of one system, defined as the ratio of EYR and ELR. As described above, ESI was corrected to AESI to consideration of structure of imported input and adverse and positive effects of rice production on the environmental. The bigger index value means the higher sustainable level, as follows.

$$AESI = \frac{AEYR}{AELR} \quad (18)$$

2.6. NUE

NUE was calculated based on rice yield and the amount of N fertilizer applied (kg kg^{-1}), and it is used to describe efficiency of nitrogen utilization in crop production systems, as follows.

$$NUE = \frac{RY_{Ni} - RY_{CK}}{F_{Ni}} \quad (19)$$

where RY_{Ni} is the crop yield that received nitrogen fertilizer in the i-th treatment (kg), i = 1, 2, 3; RY_{CK} refers to the crop yield of CK without fertilization (kg), and F_{Ni} means the amount of nitrogen fertilizer applied in the i-th treatment (pure nitrogen, kg).

2.7. Economic assessment

Economic assessment can provide the economic performance of rice production systems by focusing on the market competitiveness of rice products. In this study, benefit to cost ratio (BCR) was considered. BCR was calculated by the ratio of total economic benefit to total economic costs. The higher value of BCR reflects the stronger market competitiveness of a production system. Therein, the economic benefit (EB) equals to the total economic output minus the total economic costs (EC) during the rice production. Furthermore, in order to monetize environmental effects and incorporate them into economic assessments, two new indicators, environmental effects per unit cost (EEPUC) and adjusted benefit to cost ratio (ABCR) were considered. Firstly, monetizing environmental effects can be completed through emergy-to-money ratio (EMR) using the following formula.

$$EnE = \frac{Em_{NEE}}{EMR_{2018}} \tag{20}$$

where EnE refers to economic value of net environmental effects ($); Em_{NEE} is net environmental effect (sej), attained using Formula (13); EMR_{2018} means the emergy-to-money ratio in 2018 (2.59E+12 sej $\$^{-1}$), detailed calculation was shown in SM. 5. EnE>0 means potential positive economic benefits, EnE<0 stands for potential economic loss. Then, EEPUC and ABCR can be calculated as follows.

$$EEPUC = \frac{EnE}{EC} \tag{21}$$

$$ABCR = \frac{EB + EnE}{EC} = BCR + EEPUC \tag{22}$$

where EB is the total economic benefits of rice production system ($ ha^{-1}); EC refers to the total economic costs ($ ha^{-1}) of rice production system.

2.8. SCD

In order to evaluate the comprehensive performance based on agronomic, economic, and environmental indicators, a compound index – SCD (system coordination degree), based on environmental sustainability, nitrogen use efficiency and economic performance of rice production systems, was established; therein, each indicator was given the same weight, and then the standardized scores were added to obtain the index value of SCD. The larger the index value, the higher the system coordination degree is, reflecting its better comprehensive performance. This index can be calculated as follows. Firstly, data standardization can be achieved by using the min-max normalization method according to Formula (23).

$$Y_i = \frac{X_i - \min\{X_i\}}{\max\{X_i\} - \min\{X_i\}} \tag{23}$$

where Y_i is standardized number value of AESI or NUE or ABCR, and the value is between 0 and 1; X_i is the corresponding raw data of AESI, NUE and ABCR in the i-th treatment; min and max are the minimum and maximum values of AESI, NUE and ABCR in all treatments, respectively. After the completion of data standardization, the SCD can be computed using Formula (24). The larger value of SCD means a better comprehensive performance of one production system.

$$SCD_i = Y_{NUE,i} + Y_{ABCR,i} + Y_{AESI,i} \tag{24}$$

2.9. Data sources and processing software

The raw data of renewable inputs, including sunlight, wind, and rainfall, were obtained from Yanting Agro-ecological Station of Purple Soil of Chinese Academy of Sciences. Agricultural materials data were gathered through field records and surveys during the growing season. The price of agricultural materials and rice came from dealers and market price surveys. The related UEVs came from public references or databases, and some missing ones were calculated in this study (shown in SM. 4–23). Microsoft Excel 2016 was used for data processing and charting, and energy flow diagrams were accomplished in Microsoft Visio 2016.

3. Results analysis and discussion

3.1. Emergy flows

Detailed emergy evaluation results for each treatment were shown in SM. 24, and their emergy flows were summarized in Fig. 4. For CK, total emergy input was 5.08E+15 sej yr^{-1}, the contribution of renewable resources to total emergy was 3.88%. Local nonrenewable resources accounted for 16.55% of total emergy input, derived from topsoil loss. Emergy derived from imported agricultural materials was the highest, with a share of 79.57%. Therein, services contributed the largest share (38.21%), followed by labors (31.37%), fuel (7.62%), electricity (1.63%), and other resources (<1%).

For N1, total emergy input reached 8.01E+15 sej yr^{-1}; therein, the share of local renewable resources was 2.46% and local nonrenewable resources contributed 10.50%. The largest contributor was imported inputs with the share of 87.04%; therein, contribution of services reached 32.80%, followed by labors (28.71%), nitrogen fertilizer (13.24%), fuel (4.83%), phosphoric fertilizer (4.64%), potash fertilizer (1.31%), electricity (1.03%), and others (<1%).

For N2, total emergy input was 7.85E+15 sej yr^{-1}; therein, the contribution of local renewable resources was 2.51%, local nonrenewable resources accounted for 10.71%. Likewise, the largest contributor was imported agricultural materials, with the share of 86.78%; therein, services contributed the largest (36.30%), followed by labors (23.68%), nitrogen fertilizer (14.26%), fuel (4.93%), phosphoric fertilizer (4.74%), potash fertilizer (1.34%), electricity (1.05%), and others (<1%).

For N3, total emergy input was 7.62E+15 sej yr^{-1}; therein, the share of local renewable resources was 2.59%, local nonrenewable resources accounted for 11.04%, and the rest came from the imported agricultural materials (86.38%). In terms of contribution of different imported input items, services accounted for 34.74%, followed by labors (24.41%), nitrogen fertilizer (14.30%), fuel (5.08%), phosphoric fertilizer (4.88%), potash fertilizer (1.38%), electricity (1.09%), and other imported inputs (<1%).

Among the four treatments, total emergy followed the trend of N1 > N2 > N3 > CK. Particularly, emergy derived from imported inputs (accounted for about 80%) was the highest among the four treatments, which illustrated the high dependence of rice production systems on the imported resources, mainly from the L&S. For the four treatments, lots of manpower investment is required in this area characterized by hilly and mountainous, where land fragmentation is common and thus restricts the local mechanization and large-scale intensive production. Similar results also appeared in related studies (Ali et al., 2019; Moonilall et al., 2020). Moreover, the diverse proportion of labors among the four systems roots in the different fertilization schemes. The advantages of one-time fertilization of CRNF could save more manpower (Xiao et al., 2019), while more manpower is required for single urea

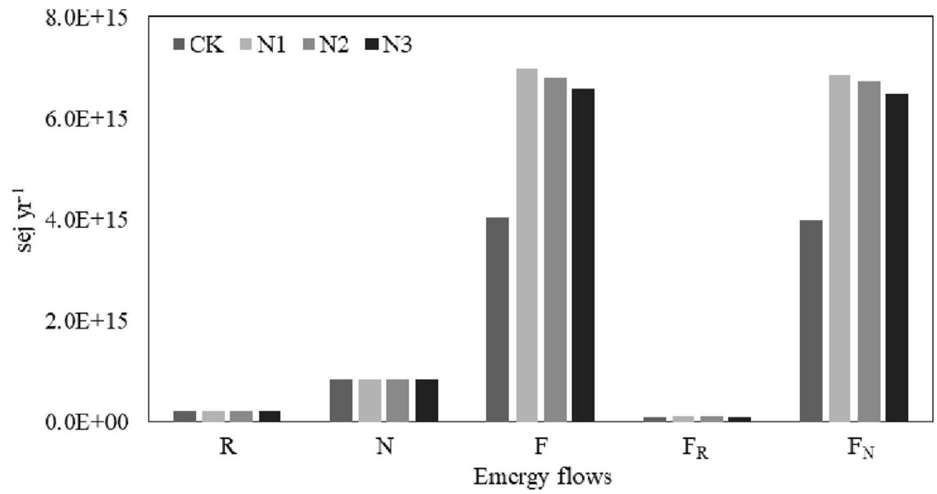

Fig. 4. Emergy flows of four treatments. R: local renewable resources; N: local nonrenewable resources; F: imported inputs; F_R: renewable imported inputs; F_N: nonrenewable imported inputs.

application due to additional topdressing. The difference in market price between urea and CRNF directly leads to a different proportion of services.

3.2. BES and adverse emissions' impacts

Results of BES and adverse emissions' impacts were shown in Table 3. As for BES, groundwater recharge was the main contributor (83.33%–86.41%) followed by net carbon sequestration (13.59–16.67%). Regarding adverse emissions' impacts, all the emergy losses were caused by NH_3 with the trend of N1>N3>N2>CK. ESE was mainly used to dilute CH_4 in CK and N2 while it was mainly used to dilute NH_3 in N1 and N3. Therefore, the key to reduce emergy loss is to inhibit the ammonia volatilization through improving the efficiency of nitrogen use.

Comparatively speaking, results of beneficial ecological service indicate that N1 has the largest contribution to ecological conservation while emergy loss of N1 was also the highest. Results of ESE showed that N1 has largest extra environmental load, followed by N3, N2 and CK. Results on net environmental effects indicated emergy loss weakens environmental benefit clearly in N1 though N1 achieves the highest BES.

Table 3
BES and emissions' impacts of four treatments (sej yr^{-1}).

Names	CK	N1	N2	N3
1. Em_{WR}	7.50E+14	7.50E+14	7.50E+14	7.50E+14
2. Em_{NCS}	1.18E+14	1.50E+14	1.47E+14	1.46E+14
Em_{BES}	8.68E+14	9.00E+14	8.97E+14	8.96E+14
3. EL_{NH3}	1.05E+13	1.71E+14	1.18E+13	5.23E+13
EL	1.05E+13	1.71E+14	1.18E+13	5.23E+13
4. ESE_{CH4}	8.36E+09	7.41E+09	9.85E+09	1.12E+10
5. ESE_{CO2}	8.83E+07	1.33E+08	1.35E+08	1.38E+08
6. ESE_{NH3}	4.81E+09	7.84E+10	5.41E+09	2.40E+10
ESE	8.36E+09	7.84E+10	9.85E+09	2.40E+10
Em_{EE}	8.57E+14	7.29E+14	8.85E+14	8.44E+14

Note: Em_{WR}: emergy of groundwater recharge; Em_{NCS}: emergy of net carbon sequestration; Em_{BES}: emergy of beneficial ecosystem services (BES), equals the sum of Em_{WR} and Em_{NCS}; EL_{NH3}: emergy loss caused by NH_3; EL: emergy loss caused by environmental emissions, here equal to EL_{NH3}; ESE_{CH4}: ecological services' emergy to dilute CH_4; ESE_{CO2}: ecological services' emergy to dilute CO_2; ESE_{NH3}: ecological services' emergy to dilute NH_3; ESE: total ecological services' emergy to dilute air emissions, equal to the maximum value among ESE_{CH4}, ESE_{CO2} and ESE_{NH3}; Em_{EE}: emergy of net environmental effects that equals to differences between Em_{BES} and the sum of EL and ESE.

3.3. Emergy indicators

Emergy indicator values of four treatments were exhibited in Table 4. UEVs for four treatments followed the trend of N1 > N3> N2 > CK, which showed that urea application reduced the resource efficiency of the system to different degrees compared to CK; therein, local fertilization scheme (N1) reduced resources efficiency by 47.37%, followed by partial replacement (N3, 37.65%) and total replacement (N2, 34.82%) of urea by CRNF, respectively. However, compared to N1, CRNF utilization can still raise resources efficiency accordingly (8.52% for N2 and 6.59% for N3). The highest R% appeared in CK (5.37), followed by while N3 (3.85), N2 (3.80), and N1 (3.78), showing nitrogen fertilizers application decreased renewability of rice productions obviously. Comparatively speaking CRNF application can slightly improve renewability of rice production systems compared to single urea application. EYR of CK, N1, N2, and N3 were 1.26, 1.15, 1.15, 1.16, respectively, while AEYR of CK, N1, N2, and N3 were 1.44, 1.23, 1.26, and 1.26, respectively. It is found that nitrogen fertilization application cut yield rate of rice production by 7.94–8.73% for EYR and 12.5–14.58% for AEYR; meanwhile, when considering emissions' impacts, AEYR grew by 9.10%–16.89% in all treatments compared with the classic EYR, reflecting net ecological benefit promote yield rate of rice production. Comparatively CRNF has slightly larger ecological benefit than single urea fertilization. For AELR, this indicator value had no obvious change before and after considering the extra ecological services. Due to the large share of imported agricultural materials in the four treatments, they are facing enormous environmental pressure. Comparatively speaking, partial replacement (N3) of urea by CRNF has the lowest environmental load among the three nitrogen fertilization schemes, followed by total replacement (N2). And this shows that CRNF utilization can mitigate environmental press to different degree. ESI measures the sustainability of a system, i.e. the larger value of ESI means the higher sustainability level. When the impacts of BES, EL, and ESE were considered, AESI was improved by 9.10%–16.89%. CK performed the highest sustainability level in the four treatments (ESI of 0.07130 and AESI of 0.08341), followed by N3, N2 and N1.

Comparisons of emergy indicators show that CRNF utilization can improve environmental sustainability of rice production to different degree compared to single nitrogen fertilizer utilization, which is mainly due to enhanced emergy yield rate.

Table 4
Emergy based indicators of four treatments.

Items	CK	N1	N2	N3
Unit emergy value (UEV, sej kg^{-1})	2.47E+11	3.64E+11	3.33E+11	3.40E+11
The renewable fraction (R%)	5.37	3.78	3.80	3.85
Emergy yield ratio (EYR)	1.26	1.15	1.15	1.16
Adjusted emergy yield ratio (AEYR)	1.47	1.25	1.28	1.29
Change ratio of EYR (%)	16.89	9.10	11.28	11.07
Environmental loading ratio (ELR)	17.61	25.45	25.32	24.95
Adjusted environmental loading ratio (AELR)	17.61	25.45	25.32	24.95
Change ratio of ELR (%)	00.00	00.00	00.00	00.00
Emergy sustainability index (ESI)	0.07136	0.04515	0.04551	0.04640
Adjusted emergy sustainability index (AESI)	0.08341	0.04926	0.05065	0.05153
Change ratio of ESI (%)	16.89	9.10	11.28	11.07

3.4. Rice yield, NUE and economic analysis

Rice yield per area (kg ha^{-1}) varied among the four treatments to different degrees (Table 5). Therein, the yield of CK (6273.84) is clearly lower than the fertilization treatments (N1 (8470.82), N2 (9436.80), and N3 (9144.92)), which showed that utilization of nitrogen fertilizer promoted rice yield by 35.02–50.42%. Furthermore, single CRNF utilization (N2) and CRNF mixed with urea (N3) produced 11.40% and 7.96% higher yield than single urea application (N1), respectively, which could be derived from the synchronization of nitrogen nutrient release and plant growth needs (Sui et al., 2013).

NUEs of N1, N2 and N3 were shown in Table 5. It was found that N2 achieved the highest nitrogen efficiency (21.09%), followed by N3 (19.14%) and N1 (14.65%) respectively under the condition of the same nitrogen application level. This reflects that CRNF utilization raises nitrogen utilization efficiency to different degrees because the nutrition supply of CRNF sustains for a prolonged time while nutrition supply of urea sustains mainly at the early stage of rice production (Zhang et al., 2018b; Zheng et al., 2017).

Detailed economic information of the four rice production systems was shown in Table 5. Therein, N2 needed the largest investment of \$1101.36 ha^{-1} due to the higher price of CRNF while it received the highest economic benefit of \$2039.52 ha^{-1} due to the highest rice yield. N3 ranked the second in the cost and benefit, with the value of \$1024.18 and \$2019.52, respectively, followed by N1 and CK. According to the results of BCR as well as unit production cost, N3 was the most competitive, followed by N2, while N1 and CK had approximate economic competition ability. Environmental benefit followed the trend of N2>CK > N3>N1 while the EEPUC followed the trend of CK > N3>N2>N1. Compared with BCR, ABCR increased by 24.74% for CK, 15.60% for N1, 16.76% for N2, and 16.13% for N3. EEPUC of N2 and N3 were 11.90% and 14.68% higher than that of N1, respectively, while the costs of N2 and N3 was only 8.52% and 0.92% higher than N1, respectively.

All the results showed CRNF application has positive effects on nitrogen efficiency, economic performance, and environmental benefit of rice production compared to single urea application, which have also been confirmed in relevant studies (Geng et al., 2015; Li et al., 2015; Lyu et al., 2015). Increasing nitrogen efficiency is the key to ensuring yield, reduce nitrogen loss and mitigate the adverse environmental impact of nitrogen fertilizer application (Alhaj Hamoud et al., 2019). Nitrogen fertilizer with higher efficiency has more application potential. Meanwhile, from the perspective of growers, economic factors are the most attractive, and this means low investment and high returns are the best choices, which means the scheme with higher BCR is more competitive. Here N3 performed the best economic performance. Besides, N3 is superior to than N1 and N2 in terms of EEPUC. Generally N3 is the optimal scheme for local rice production.

3.5. SCD

Under the dual pressures of food security and environmental protection, the contradiction between environmental sustainability, agronomic benefit and economic benefit is highlighted. The three perspectives do not exist in isolation but interact with one another. As shown in Fig. 5, among the three fertilization treatments (N1, N2 and N3), the index value of N3 ranked first due to the higher level of ABCR and AESI, followed by N2 and N1. Comparatively, SCD of N1 was worst due to the lowest performance in three aspects. Overall, partly replacement of urea by CRNF has the best comprehensive performance based on environmental sustainability, agronomic benefit and economic benefit.

However, the following obstacles still restrict wide application of CRNF especially in developing countries (Shaviv, 2001), including (1) high price of CRNF, which is still the main constraint. At present, price of the mainstream CRNF is about \$450 t^{-1}, which is still higher than related conventional fertilizer products (about \$360 t^{-1}) in China. Here it was found that environmental benefit per unit cost of N2 and N3 were higher than N1. Compared with N1, increased extra environmental benefit per kilogram CRNF product for N2 and N3 were \$0.18 and \$0.12 (extra environmental benefit brought by CRNF of N2 and N3 were \$60.33 ha^{-1} and \$24.18 ha^{-1} respectively, and application amount of CRNF were 341 kg ha^{-1} and 205 kg ha^{-1} for the two schemes respectively), and they are 40% and 27% of the price of CRNF respectively. This can also act as a reference for fiscal subsidies, i.e. subsidizing 30%–40% of the market price to farmers to encourage them to use CRNF. Similar measures have been implemented in Guangdong province, China, where the local

Table 5
Results of nitrogen use efficiency (NUE) and economic benefit.

Treatments	Yield (kg ha^{-1})	NUE (kg kg^{-1})	Cost (\$ ha^{-1})	EnB (\$ ha^{-1})	BCR	EEPUC	ABCR
CK	6273.84	–	749.92	1338.19	1.784	0.441	2.226
N1	8470.82	14.65	1014.83	1804.51	1.778	0.277	2.055
N2	9436.80	21.09	1101.36	2039.48	1.852	0.310	2.162
N3	9144.92	19.14	1024.18	2019.52	1.972	0.318	2.290

Note: NUE: nitrogen use efficiency; EnB: environmental benefit; BCR: benefit to cost ratio; EEPUC: environmental effects per unit cost; ABCR: adjusted benefit to cost ratio.

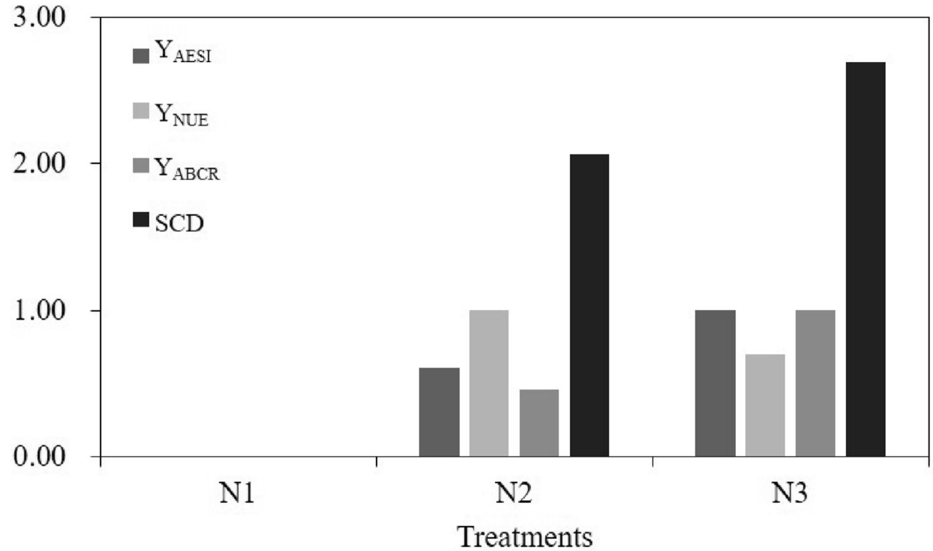

Fig. 5. System coordination degree (SCD) of three fertilization treatments. Y_{AESI}, Y_{NUE} and Y_{ABCR}, refer to the standardized value of adjusted emergy sustainability index, nitrogen use efficiency and adjusted benefit and cost ratio, respectively; SCD is the system coordination degree.

government will subsidize farmers 25–30% of market prices in 2020 for promoting application of the CRNF (Department of Agriculture and Rural Affairs of Guangdong Province, 2020); (2) poor cognition of farmers on CRNF. Through field investigation, it is found that the cognition of farmers on CRNF is still very poor, so the popularization of CRNF needs the promotion of relevant local governmental departments through publicity and education, technical guidance besides fiscal subsides; (3) some technical issues need to be well addressed. For example, as for the production chain of polyurethane-coated CRNF in this study, the viscosity problem of curing bed needs to be overcome. Meanwhile, polymer coating processes are quite complex and involve numbers of chemicals; therein, organic solvents are used to prepare a coating solution through specific equipment. All these rigid requirements of technology and equipment affect the enthusiasm of fertilizer enterprises, and thus reduce economic attractiveness of CRNF (Azeem et al., 2014), and (4) lacking effective market supervision. It is reported that there are about one hundred so-called CRNF enterprises in China, and they provide all kinds of products with different quality and prices. However, effective market supervision is lacking. Therefore, it is often difficult for farmers to choose qualified CRNF products, which limits further application of CRNF in crop production.

4. Suggestions

(1) **Promoting farmers' awareness and acceptance degree of CRNF.** On the one hand, efforts need to be made by the local agricultural department to popularize partial replacement of urea by CRNF in rice production through the establishment of relevant information network and CRNF promotion and application center so as to improve farmers' awareness and acceptance degree, which can be implemented with the help of media such as radio, television, especially the internet. On the other hand, fertilizer enterprises or distributors should develop targeted promotional services or establish demonstration bases through cooperation with farmers to raise the acceptance degree of CRNF. These measures will enrich farmers' cognition of CRNF from concept to practical effects, especially the performance on the rice yield and economic, which are conducive to push forward wide utilization of CRNF. In a long run, this will contribute to enhancing the NUE, saving manpower as well as reducing adverse environmental impacts from single urea application for increasing the sustainable level of rice production.

(2) **Financial and policy supports for popularization of CRNF application.** Nowadays, the price of CRNF is always restricting the industrial development of CRNF and farmers' acceptance degree. The government's tax reduction or exemption, and preferential loans should be offered to the excellent enterprises that are committed to improving and expanding their CRNF products. Moreover, in order to avoid the excessive speculation of enterprises, there should be an assessment or supervision system to ensure their products' quality. For farmers, according to the study result, the financial subsidy recommended is 30–40% of the market price of CRNF products. These measures will reduce production cost of CRNF enterprises and enhance their competitiveness in the short period. Meanwhile, they will promote application of CRNF products in crop production and then mitigate non-point source pollution caused by singe urea application while guaranteeing grain yield.

(3) **Enhancing technical level of CRNF industry and improving terminal market supervision.** Firstly, fertilizer enterprises should pay more attention to technical progress to break through technical bottlenecks. For instance, to solve viscosity problem of curing bed during polyurethane-coated CRNF production, some measures could be considered, such as installing a baffle in the fluidized bed (Li et al., 2020), using dual fluidized bed gasification systems (Hanchate et al., 2020), controlling the addition rate of reactive materials etc. Secondly, to improve market supervision of CRNF, the related governmental departments should regularize CRNF registration certificates and strengthen production inspection. Based on the standard of ISO (2016), specific regulations on resource consumption and environmental discharge of CRNF production should be formulated. In the short term, these measures need extra economic investment of enterprises. In the long run, these measures could promote sustainable development of the CRNF industry and thus improve the sustainable level of crop production.

5. Strengths and limitations

A comprehensive evaluation was carried out in this study by innovatively merging the BES, EL, and ESE into EMA as well as integrating environmental, agronomic, and economic indicators into a comprehensive index SCD. EMA is an effective tool to assess environmental sustainability through qualitative and quantitative classification of resources invested in a system. However, this also leads to potential uncertainty. In the process of emergy evaluation, the accuracy and representation of UEVs can affect the evaluation results. One agricultural ecosystem is a complicated system that connects human society and the environment. Updating the UEVs in a targeted manner can improve the accuracy of emergy evaluation results according to the temporal and spatial characteristics of the system being investigated. This study adopted field survey data and laboratory monitoring data to ensure reliability of basic data; meanwhile, some essential UEVs were updated through reliable databases to strengthen their pertinence. And all these works made the evaluation results more accurate.

However, all the evaluation results could be still limited due to only one-year data and limited application scale. Future research should concentrate on a longer period of time and a larger scale, so as to provide more sufficient policy-making information for promoting CRNF's wide application.

6. Conclusions

In summary, the following findings can be attained: (1) CRNF utilization raises environment sustainability by 2.82–4.61%; (2) CRNF utilization improves nitrogen use efficiency by 30.65–43.96%; (3) CRNF utilization enhances economic benefit by 5.21–11.44%. Generally, N3 has the best system coordination degree among the three fertilization schemes. This study provides useful information on the environmental, agronomic and economic performance of CRNF replacement or partial replacement of urea under several fertilization schemes in rice production. Rice production systems, as one kind of agricultural ecosystem dominated by humans, their positive benefit, and adverse environmental impacts should be considered simultaneously when evaluating their environmental sustainability. To address economic and nitrogen utilization related issues, the two categories of complementary indicators are also considered. Finally, the three categories of indicators are integrated into a compound index to assess comprehensive performance of rice production. Therefore, from the perspective of system-thinking, this study also provides one of the decision-making tools for evaluating other crop production systems in other regions/countries.

Author contribution statement

Yanfeng Lyu: Raw data collection, Methodology, Writing-Original draft preparation. **Xiangdong Yang**: Check of Raw data and Methodology, and revision of Original draft. **Hengyu Pan**: Check of Raw data, improvement of Methodology, and revision of Original draft. **Xiaohong Zhang**: Conceptualization, emergy analysis, the indicator system construction, Data curation, manuscript revision, Resources, Funding acquisition. **Haoxing Cao**: Preparation of Raw data. **Sergio Ulgiati**: improvement of Methodology, and revision of Original draft. **Jun Wu**: improvement of fertilization schemes. **Yanzong Zhang**: Supervision and management of the projects. **Guiyin Wang**: Software. Yinlong Xiao : Language revision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.126198.

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