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Comparing specialised crop and integrated crop-livestock systems in China with a multi-criteria approach using the emergy method

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Abstract

The dominant specialised cropping system (SCS) has supported the increasing population in China, although this agricultural production paradigm could lead to environmental problems. The modern integrated crop-livestock system (ICLS) in China, designed as a recycling paradigm, can alleviate the negative environmental impacts of SCS. However, it must be better investigated, especially due to the trade-off between increased production and environmental harm. In this study, we set up a multi-criteria evaluation with eight indicators based on emergy analysis to quantify and compare the performance of ICLS and SCS and to evaluate the performance of the indicators along a gradient when a proportion of chemical nitrogen is substituted with manure fertiliser nitrogen (PCSM). We examined one experimental modern ICLS and an average SCS by conducting a household survey in Shandong province. The results showed that the ICLS puts less pressure on the environment (ELR = 1.04), has higher emergy sustainability (ESI = 1.09), and generates higher economic benefits per unit area of land (LPO = 3789.94 \$·ha^{-1}). However, the productivity of the ICLS is lower (T_r = 1.66E+05 sej·J^{-1}, EOD = 1.07E+11 J·ha^{-1}·yr^{-1}, EYR = 1.13) than that of the SCS. With an increasing gradient of PCSM, for both systems, the productivity and environmental pressure decreased sharply; this trade-off was less marked for the ICLS. Considering sustainable resource utilisation, environmentally friendly production, and system stability, the ICLS could be an option for Chinese agricultural production in regions with serious issues of manure pollution and cultivated land degradation. However, the ICLS needs to optimise the crop-livestock structure, strengthen scientific management, and improve productivity.

Keywords: Crop-livestock integration; Manure fertiliser; Trade-off; Specialised agriculture; Environmental impacts

1. Introduction

Specialised agricultural systems (SAS), the agricultural production paradigm focusing on one or a few main products at a farm or regional level, has supported rapid population growth in China. Grain production in China has increased 1.7 times from 1980 to 2010 using specialised cropping systems (SCS) (CSY, 2011). In addition, with the increase in specialised livestock system (SLS), the livestock in China tripled between 1980 and 2010 (Bai et al., 2018). However, many studies have proven that specialised crop and livestock systems can lead to soil erosion, biodiversity loss, climate change, and water and air pollution (Peyraud et al., 2014; Ryschawy et al., 2017). SCS is unsustainable in the long run (Sneessens et al., 2016; Steinfeld et al., 2006) because of the high use of non-renewable resources (e.g., chemical fertiliser) and the high dependency on marketed inputs. For example, not only is the chemical fertiliser input to the SCS non-recyclable, but it also poses environmental risks (Spångberg et al., 2011; Wang et al., 1996). SLS induces the accumulation of concentrated livestock manure, which could be a resource for crop production, but poor management can lead to environmental issues (Bai et al., 2018; Chadwick et al., 2015). Nowadays, feed grains can be transported to livestock systems regularly, while livestock manure cannot be returned to the crop system in time, which causes the separation of crops and livestock. Chadwick et al. (2015) reported that the Chinese government needs to ensure that livestock manure is integrated into nutrient planning of the cropping system to reduce the need for chemical fertiliser (Guo et al., 2020).

The Chinese government has implemented policies to develop an integrated crop-livestock system (ICLS) (MARAPRC, 2015). Within this system, crops (e.g., corn) would serve as forage for livestock, and manure from livestock would be returned to cropland as fertiliser (Herrero et al., 2010). This paradigm can alleviate the negative impacts of SAS on the environment and decrease inputs by utilising organic fertiliser from livestock manure (Ryschawy et al., 2017). ICLS can increase economic efficiency by reducing production costs and the risk of market fluctuations (Ryschawy et al., 2017). Modern ICLS is designed based on available technology to obtain high socio-economic outputs and multiple environmental benefits in different agroecological regions worldwide (Lemaire et al., 2014).

However, replacing SAS with ICLS may require some trade-offs. As modern Chinese ICLS is still under development, it is essential to assess its performance on multiple criteria (i.e., resource utilisation, productivity, environmental pressure, and sustainability) against SAS, which is dominant in China. In addition, quantitative analysis of the performance of both ICLS and SAS, calibrated with data from a Chinese region, can shed light on their advantages and disadvantages. This will allow farmers and the government to make an educated decision according to local environmental conditions and different requirements.

Increasing the proportion of chemical fertiliser substituted with manure fertiliser (PCSM) is a direct approach to increase livestock manure consumption. In the future, increasing PCSM would not only reduce the risk of livestock manure pollution to the environment but would also reduce the reliance on non-renewable chemical fertiliser. Many studies have analysed the effects of different PCSMs on crops and soil. Regarding crop yield, Lv et al. (2020) found that a 25% PCSM substitution can simultaneously ensure crop productivity and environmental protection under a wheat-maize cropping system. For the aspect of the crop field soil, Ji et al. (2018) found that the diversity of soil microbes increased with an increase in the PCSM. However, these studies mainly focus on the field level, and the analysis of the system performance for an ICLS farm with a change in PCSM is less reported. It can be argued that increased use of manure fertiliser over synthetic fertiliser, ICLS can result in better performance. However, to the best of our knowledge, no studies have quantified these performances and showed the involved trade-offs.

Emergy analysis is a useful tool for comparing the performance of ICLS and SAS. Emergy analysis creatively combines energetics and system ecology (Zhang et al., 2016). It is an effective and robust method for evaluating system performance (Zhang et al., 2012). Since the 1990s, emergy analysis has been widely used to evaluate agricultural resource use, productivity, environmental impact, and sustainable development at various scales, including national, regional, and local agricultural systems (Cavalett and Ortega, 2009; Chen et al., 2006; Giannetti et al., 2011; Zhang et al., 2012; Zhang et al., 2016). As a universal measure of performance and sustainability for agricultural systems, emergy analysis consists of building a model through standardization of the various inputs and outputs (Odum, 1996; Zhang et al., 2016), expressing all of them in solar equivalent joules. Previous studies have used emergy analysis to assess the performance of ICLS. Some studies have focused on the biogas-linked agricultural paradigm, which mainly considers obtaining clean fuels using livestock manure. For example, Yang and Chen (2014) found that it made a positive contribution to carbon mitigation. Wu et al. (2015a) found that it has a lower economic input-output ratio in the short run. These studies suggest that emergy analysis is an efficient methodology for assessing the performance of ICLS. However, to the best of our knowledge, no existing study has used emergy analysis to compare the ICLS and SAS, and how they perform under an increasing use of manure fertiliser over synthetic fertiliser.

In this study, we used emergy analysis to compare one modern ICLS with one typical SAS, used in the Shandong province, for two purposes: (1) assessing the advantages and disadvantages of the ICLS with respect to the SAS using a multi-criteria approach; and (2) discuss how ICLS and SAS perform under scenarios of increasing the use of manure fertiliser over synthetic fertiliser. For several reasons, we decided to focus on SCS for comparison with ICLS. First, SCS, as the primary mode of production, not only supplies grain (e.g., wheat and rice) for human use but also provides feed to SLS, which is the basis for the operation of other artificial ecosystems. Second, grain self-sufficiency, which needs to be guaranteed by SCS, has always been at the heart of the national food security agenda in China (Ghose et al., 2013). Third, there is the possibility of introducing livestock to SCS in China, while the opposite is not necessarily true. Industrial livestock systems are often in peri-urban areas and do not have available land for crop integration (Li et al., 2008), such as in the capital city of Beijing (Wei et al. 2016). Therefore, bringing livestock from peri-urban areas to crops is a more feasible option.

For purpose (1), we developed a set of indicators to assess system performance along multiple dimensions. For purpose (2), we calculated the performance of some of these indicators over a gradient of an increased PCSM. Nitrogen is the main nutrient in manure fertiliser, and the main nutrient for crop production. Therefore, chemical nitrogen substitution with manure fertiliser nitrogen was considered in this study, while phosphate and potash were not considered. The results indicate the current performance of an ICLS and a typical SCS in China and provide theoretical support for the adjustment of crop-livestock structure in ICLS farms.

2. Methods

2.1 Case study

We considered Shandong Province as a case study to conduct emergy analysis of ICLS and SCS. Shandong Province is one of the most important regions of China, located on the eastern coast of China, with a latitude range of 34°25–38°23 N and a longitude range of 114°36–122°42 E (Fig. 1). The region is characterised by optimised agricultural structures and the vigorous development of economic commodities, with Shandong Province leading agricultural production in China since the end of the 1970s. In 2017, the grain yield of Shandong Province was 5.37E+07 ton, ranking third in China (CSY, 2018). Both meat (8.66E+06 ton) and egg (4.45E+06 ton) production in Shandong Province ranked first in China in 2017 (CSY, 2018). A temperate monsoon climate dominates this region, with an annual average temperature range of 11–14 °C. The average annual precipitation is generally 550–950 mm, with 60%–70% of the annual precipitation observed in summer. Sunlight is an abundant resource in this region, with an average annual insolation duration of 2290–2890 hour.

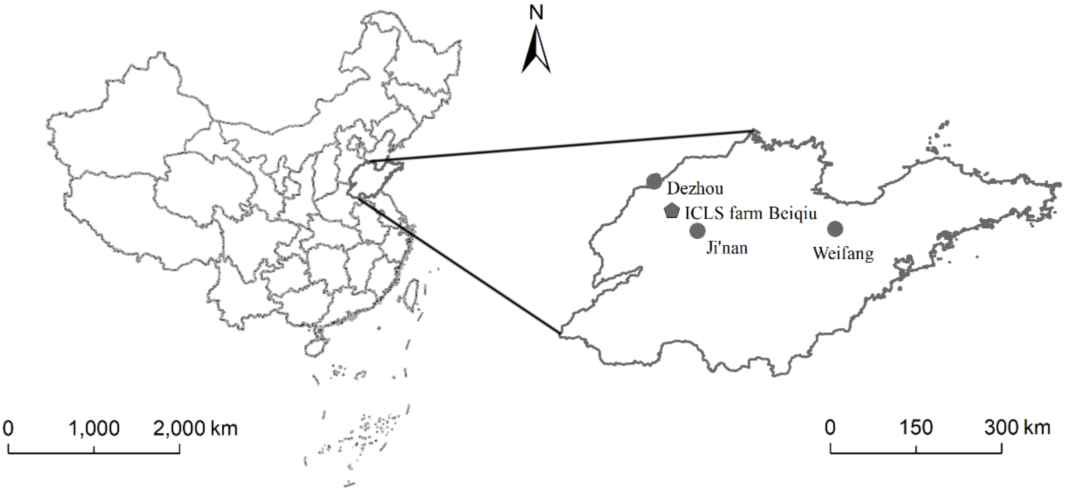

Fig. 1 The location of Shandong Province in China. The three circled sites (Ji’nan, Weifang, and Dezhou) indicate where field surveys of specialised cropping systems (SCS) were undertaken, and the pentagon site represents the location of the experimental agricultural paradigm of ICLS (Beiqiu Farm).

2.2 Data source

Data were collected for the comparison of two systems: an average crop-only system and a real farm consisting of crop and livestock integration.

2.2.1 Specialised agriculture

In this study, an SCS was chosen as a typical specialised agricultural system. The cropping system involves the annual rotation of winter wheat and summer maize, which are the dominant crops in Shandong Province. In 2017, we conducted a household survey to gather data on the cropping activities of 271 rural smallholder farming families during 2016/2017 through face-to-face interviews in Shandong Province (including the municipalities of Ji'nan, Weifang, and Dezhou, Fig.1). The average cultivated area per family was 0.53 ha. The survey data comprised cultivated land area, cropping system, material inputs, crop yield, and other cultivation-related information. The climate data of the SCS case study were obtained from the Shandong Statistical Yearbook (SSY, 2017). The inputs and outputs were the average values of all farming families included in the study.

2.2.2 Integrated crop-livestock agriculture

The ICLS was studied with the data of the Beiqiu Farm (37°00′ N, 116°34′ E), which originated from the project of Science and Technology Service Network Initiative of the Chinese Academy of Sciences, "Research and application demonstration of new paradigm farm in the Yellow River Delta (May 2014–May 2016)" and "Industry demonstration of family farm around Bohai sea (January 2017–June 2018)". This farm is still in good working order. Currently, the farm undertakes not only the functions of application demonstration but also serves as an experimental site. The farm covers an area of 15.33 ha, including an advanced semi-organic cropping subsystem (field crop region), a high-value farming subsystem (vegetable and livestock), and a non-production subsystem (processing conversion region and office region). The advanced semi-organic cropping subsystem (7.33 ha) specialises in the winter wheat to summer maize rotation. The vegetable subsystem is composed of tomatoes, cucumbers, cabbage, celery, eggplant, and green onions. Livestock mainly consists of pigs, sheep, geese, laying hens, and broilers. All livestock manure is collected using an automatic manure scraper and then converted to organic fertiliser by aerobic composting fermentation technology. This technology uses microbial activity to degrade and decompose livestock manure, with low energy consumption, a short fermentation period, and higher manure fertiliser efficiency (Ma and Wang, 2018). Organic fertiliser is supplied to crops and vegetables, while maize is crushed by machinery and converted into forage for livestock. Manure and maize are also purchased as external supplements. The data on climate and farm input and output of the ICLS case study were mainly obtained through interviews with farm managers in 2018.

2.3 Emergy analysis

Ecological energy research underwent a major transformation from energy analysis to emergy analysis (Chen, 2011). The flows of energy, materials, and labour in an agricultural system can be transformed into solar equivalent joules (sej) (Li and Brown, 2017; Zhang et al., 2012). The inputs in agricultural systems were converted using solar transformity coefficients, which represent the amount of solar emergy per unit of energy or substance (units of $sej{\cdot}J^{-1}$ or $sej{\cdot}g^{-1}$) (Liu and Chen, 2007; Odum, 1996).

Both systems were conceptualized in the framework of emergy analysis. Fig. 2a and Fig. 2b illustrate the components and interactions for SCS and ICLS, respectively, as well as the boundaries and driving sources, using the energy system language presented by Odum (1996). For the SCS, the main external emergy resource inputs in the Chinese province are groundwater, nitrogen, and phosphate, accounting for 26.02%, 23.41%, and 12.16% of the total emergy input, respectively (Supplementary Table S2). For ICLS, the main external emergy resource inputs are manure, soybean meal, electricity, plastics, and groundwater, accounting for 32.36%, 15.09%, 9.85%, 7.39%, and 6.48% of the total emergy input, respectively (Supplementary Table S3). The input of resources can be categorized as follows: local renewable resources (R), such as sun, rain, and earth cycles; local non-renewable resources (N) that are not replaced within an annual cycle, such as local soil and groundwater; purchased (renewable and non-renewable) resources (F), such as machinery, chemical fertiliser, pesticides, seeds, labour, and other external resources (David et al., 2018). The renewability coefficient was introduced to divide each purchased resource into renewable and non-renewable fractions. The renewability coefficient in this study was based on previous studies, or the authors' estimations (Agostinho et al., 2008; Cavalett et al., 2006; Wu et al., 2015a; Wu et al., 2015b). The purchased resources were divided into two types: materials (M) and labour (L). As an input resource, livestock manure consists of organic matter and nutrients, which are beneficial to crops. The agricultural production system would reduce external resource input (e.g., nitrogen) if livestock manure could be supplied within the system (i.e., ICLS). By contrast, the production system will utilise chemical nutrients (i.e., SCS) or increase external resource input if the agricultural production system requires manure fertiliser than other systems. All inputs of energy, materials, and labour were processed by converting mass quantities (g or kg) and energy (J) into emergy units by applying transformity coefficients (Zhang et al., 2012). The yield (Y) of agricultural products consists mainly of wheat, maize, meat, egg, and vegetables; therefore, all the products were converted into energy (J) to allow comparability. According to the theory of emergy accounting, the total emergy input (U) needed to support a production system is equal to the total emergy output (Hu et al., 2010).

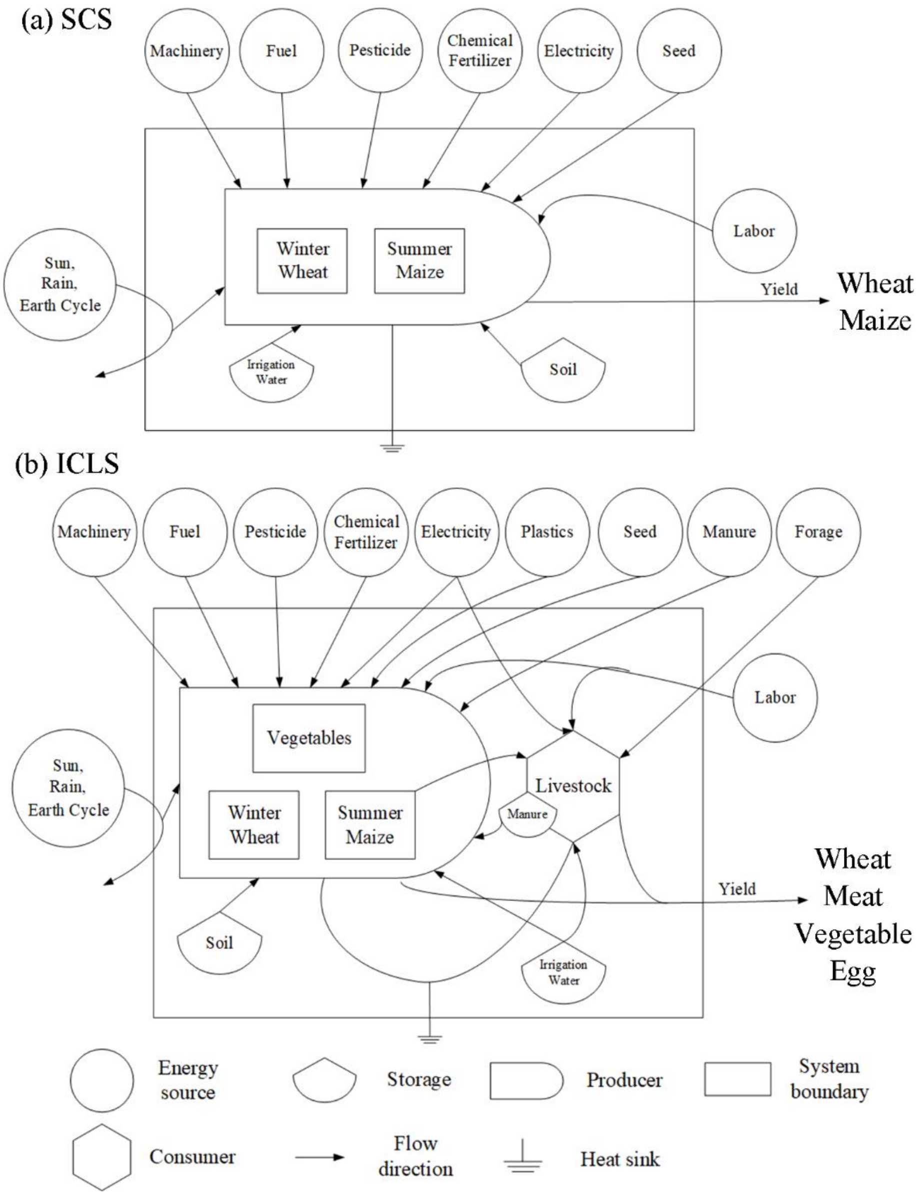

Fig. 2 The energy flows of (a) SCS and (b) ICLS paradigms.

In this study, the following assumptions were important in emergy calculation. (1) All the transformity coefficients in this study refer to the 12.00E+24 sej·yr^{-1} emergy baseline, which is the main driving emergy flow in the geobiosphere (Brown and Ulgiati, 2016). (2) Groundwater is mainly used for agricultural production in the SCS and ICLS, and it is considered a non-renewable resource due to its scarcity and slow turnover (Zhang et al., 2012). (3) To make the agricultural systems comparable, each type of input is converted into solar equivalent joules per unit area per year (sej·ha^{-1}·yr^{-1}), and all the outputs are converted to energy (J·ha^{-1}·yr^{-1}); detailed parameters or formulae can be found in Supplementary Table S1. (4) Seed inputs for the SCS and ICLS were different, each having a specific transformity; the main types of seeds were wheat, maize, and vegetables. However, we used the same transformity to calculate the emergy for different seeds. The main reasons are as follows: the difference in transformity among the seeds is negligible, and the emergy input of seeds accounts for a small proportion of the entire agricultural system. For example, the emergy input from seeds accounted for only 2% and 3% of the total emergy flows in wheat and maize production systems, respectively (Wang, X.L. et al., 2014).

2.4 Performance indicators

For assessing the advantages and disadvantages of the ICLS with respect to the SAS using a multi-criteria approach, a set of eight basic emergy indicators was defined (Table 1). These indicators can be calculated from emergy input terms and energy output terms and can be organized into different categories: resource utilisation, productivity, environmental pressure, and emergy sustainability. Some indicators could be considered benefits (higher values indicated better situations), while other indicators could be considered costs (higher values indicated worse situations). The indicators, which were calculated by the input and output resources and per unit area of land, can be comparable even for farms of different sizes and compositions. The farms representing the SCS paradigm in the region hardly used manure fertiliser (PCSM = 0%), as almost all nitrogen quantities come from chemical fertilisers, whereas ICLS was designed to decrease manure pollution and utilise more manure fertiliser. According to the ratio of total nitrogen supply from manure fertiliser and total nitrogen demand for crops in the experimental farm, the quantity of manure fertiliser application can support approximately 70% of PCSM in ICLS.

2.4.1 Resource utilisation

Resource utilisation, which describes both the resource input of intensity and the resource input of dependence on external economic systems, consists of total emergy input (U) and purchased emergy resource input (F). The total emergy input is defined as the sum of all the emergy inputs, including local renewable resources, local non-renewable resources, and purchased (renewable and non-renewable) resources, which support the entire production system. This indicator describes the resource input intensity of an agricultural production system. Purchased emergy resources are the input emergy resources related to human social economics, which are outside the production system. The higher the purchased emergy resources, the more economic cost input outside the agricultural production system, and the system will less likely be self-sufficient.

2.4.2 Productivity

Four indices were selected to evaluate different aspects of productivity: transformity (Tr), energy output density (EOD), land profit output (LPO), and emergy yield ratio (EYR). These indicators describe productivity from different viewpoints: the transformity of the production system is one of the basic indices of emergy analysis and is calculated from the viewpoint of emergy and energy (Odum, 1996). The energy output density mainly considers energy, the land profit output mainly considers economic benefits, and the emergy yield ratio mainly considers emergy return on emergy investment. For the system production efficiency, transformity (sej·J^{-1}) is defined as the total emergy input (sej) divided by the available energy of products (J), which can measure the amount of resources required to produce one unit of product and corresponds to the inverse of energy production efficiency. The higher the transformity of products, the lower the efficiency of system production. The energy output density (J · ha^{-1} · yr^{-1}) is defined as the available energy of products (J) in the unit area per year, which is a land productivity indicator that measures the quantity of energy production of one system per unit area of land per year. The land profit output measures the economic benefit of one system per land area per year (Supplementary Table 4). The emergy yield ratio is defined as the total emergy input divided by purchased emergy, which measures the emergy return on the emergy investment and indicates the ability of a process to exploit local resources (i.e., local renewable resources and local non-renewable resources) by investing outside economic resources. The higher the emergy yield ratio, the higher the emergy return on the emergy investment, indicating a stronger possibility of exploiting local resources.

2.4.3 Environmental pressure

The environmental loading ratio (*ELR*) is the ratio of non-renewable emergy resources to renewable emergy resources, indicating the stress to the environment. The higher the ratio, the greater the pressure on the environment.

2.4.4 Sustainability

The emergy sustainability index (*ESI*) is defined as the emergy yield ratio divided by the environmental load ratio, showing the contribution of a process to the economy per unit of the environmental impact that it generates (David et al., 2018; Brown and Ulgiati, 1997).

283 Table 1 Emergy terms and performance indicators calculated for comparing the SCS and ICLS paradigms.

Name	Category	Unit	Formula	Description
Emergy terms				
Local renewable resources	/	$sej \cdot ha^{-1} \cdot yr^{-1}$	R	Local free renewable flows directly available to the system, such as sun, rain, and earth cycle.
Local non-renewable resources	/	$sej \cdot ha^{-1} \cdot yr^{-1}$	N	The environmental resources that are not replaced within an annual cycle, such as local soil and groundwater.
Purchased resources	/	$sej \cdot ha^{-1} \cdot yr^{-1}$	$F = M + L$	Imported resources from the external economic systems, including materials (M) and labors (L).
Purchased materials resources	/	$sej \cdot ha^{-1} \cdot yr^{-1}$	$M = M_R + M_N$	Imported materials from the external economic systems, which are divided into a renewable

				fraction (M_R) and a non-renewable fraction (M_N) according to their renewability factor.
Labour	/	sej·ha^{-1}·yr^{-1}	$L = L_R + L_N$	Imported labours from the economy, which are divided into a renewable fraction (L_R) and a non-renewable fraction (L_N) according to their renewability factor.
Performance indicators				
Total emergy input	Resources utilisation	sej·ha^{-1}·yr^{-1}	$U = R + N + F$	Total emergy flows needed to support a production system (i.e., total emergy input resources). The total emergy input is equal to the total emergy output.

Transformity	Productivity	sej·J^{-1}	$T_r = \frac{U}{E_p}$	[a] The system production efficiency that the total emergy input divided by the available energy of the products. The higher the transformity of a system, the lower its production efficiency. E_p (J · yr^{-1}) represents the available energy of the products for a system. The higher the E_p, the more production of energy for a system.
Energy output density	Productivity	J·ha^{-1}·yr^{-1}	$EOD = \frac{E_p}{area}$	The available energy outputs in the unit area per year, indicating the land energy output efficiency for the land per year.
Land profit output	Productivity	\$·ha^{-1}·yr^{-1}	$LPO = \frac{TEO - TEI}{area \times year}$	The profit output in a unit area of land per year, indicating the land economic output efficiency for the unit area per year. TEO is the total economic

				output value and TEI is the total economic input value.
Emergy yield ratio	Productivity	/	$EYR = \frac{U}{F} = 1 + \frac{R + N}{F}$	The total emergy input is divided by the purchased emergy imported, indicating the emergy return on emergy investment. Also, $R + N$ is the total local emergy resources that don't need cost, so EYR also can indicate the system's ability to utilise local resources (do not need cost) by investing in purchased resources from the outside.
Environmental loading ratio	Environmental pressure	/	$ELR = \frac{N + M_N + L_N}{R + M_R + L_R}$	The ratio of the total non-renewable emergy resources to the total renewable emergy resources, indicating the stress to the environment. The

				higher the ratio, the larger the pressure on the environment.
Emergy sustainability index	Sustainability	/	$ESI = \frac{EYR}{ELR}$	[b] The ratio of the emergy yield ratio EYR to the environmental load ratio ELR, showing the contribution of a process to the economy per unit of the environmental impact that it generates. The larger the ESI, the higher emergy sustainability of the production system.

[a] The definition refers to Odum (1996).

[b] The definition of ESI refers to David et al. (2018) and Brown and Ulgiati (1997).

2.5 Influence of the manure-synthetic fertiliser substitutability

We calculated the effect of substituting synthetic fertilisers with manure to different degrees. We defined the proportion of chemical fertiliser substituted with manure fertiliser $PCSM = NM/TN$ as the nitrogen supplied by manure fertiliser (NM) divided by the total nitrogen demand (TN). Once the total nitrogen demand was calculated for the assigned value of $PCSM$, it was possible to calculate the demand for chemical fertiliser nitrogen ($NC = TN \times (1 - PCSM)$) and manure fertiliser nitrogen ($NM = TN \times PCSM$) for the two systems.

The total nitrogen demand was calculated with:

$$TN = \sum_{i} P_i \times ND_i \tag{1}$$

In this equation, which follows MARAPRC (2018), P_i (kg) is the production of crop i, ND_i (kg · kg^{-1}) is a constant coefficient representing the quantity of nitrogen demand per unit production of crop i. We considered three main categories of cultivated crops (wheat, maize, and vegetables), whose nitrogen demand coefficients are listed in Supplementary Table S5.

Fresh livestock manure cannot be directly utilised by crops and vegetables. Fresh livestock manure needs to be fermented and converted into manure fertiliser (MF). The MF can be calculated as follows:

$$MF = \frac{NM}{NCO} \tag{2}$$

where NCO (%) is the nitrogen content of manure fertiliser. In this study, NCO was 1.75%, which is the surveyed data.

The demand for total fresh livestock manure (TM) can be calculated by:

$$TM = MF \times MCC \tag{3}$$

where MCC is the conversion coefficient from fresh manure to manure fertiliser. In this study,

$MCC = 3$, which is the survey data from the experimental farm.

To calculate the emergy terms, *TM* cannot be used directly. In this study, we assumed that if the fresh manure from the internal agricultural system (ML) is not sufficient at a certain level of *PCSM*, unmet demand for fresh manure would be addressed by an external agricultural system (ME) by default, as a purchased resource, $ME = \max(0, TM - ML)$. The ML was calculated as follows:

$$ML = \sum_{i} EC_i \times T_i \times Q_i \tag{4}$$

where EC_i (kg · head^{-1} · day^{-1}) is the excretive coefficient of livestock species i, T_i (day) is the time period of the growth cycle of livestock species i, Q_i (head) is the quantity of livestock species i. The detailed coefficients are listed in Supplementary Table S6.

When $ME \geq 0$, fresh manure resource input was purchased. For emergy accounting of agricultural systems, we mainly considered the organic matter and nitrogen in the ME. The amount of organic matter input (OMI, kg) for crops was calculated as follows:

$$OMI = \frac{ME}{MCC} \times OMC \tag{5}$$

where OMC (%) is the organic matter content of manure fertiliser. In this study, the *OMC* was 37.5%, from the surveyed data. OMI and NM correspond to renewable resources; their variation would impact the terms of M_R and M_N (Table 1) and then change other indicators affected directly or indirectly by the terms M_R and M_N. Livestock manure is a locally available resource (therefore accounted for in internal resources), while the manure would be imported (accounted for in the purchased resources) if the demand exceeds locally available supply.

As an assumption, we did not treat the surplus manure as a pollutant or a product because we did not have enough information on manure management to accurately represent it. For example, livestock manure would be the product (i.e., organic fertiliser) if the farm converted the surplus manure into fertiliser; inversely, livestock manure would be the pollutant, as emergy accounting would be difficult if the farm discards the manure. Therefore, our analysis focuses on the effect of the PCSM on resource use for the two systems. In addition, crop production was assumed to be constant. Previous studies have shown the effects of different substitutions of chemical fertiliser with manure fertiliser on crop yield (Geng et al., 2019; Lv et al., 2020). However, the difference was less than 12% between the highest and lowest yield treatment, which adopted different substitutions of chemical fertiliser with manure (Geng et al. 2019). Therefore, the change in crop yield from different proportions of chemical fertiliser substitution with manure was not considered in this study.

For the two systems, we explored the effect of values ranging from a 0–100% PCSM on four indicators: transformity, emergy yield ratio, environmental load ratio, and emergy sustainability index, which are sufficient to simulate the performance of system production efficiency, productivity, environmental pressure, and emergy sustainability, respectively. For the other indicators, the energy output density and land profit output did not change.

3. Results

We compared the performance of the two systems on all the indicators chosen for the multi-criteria assessments, and then explored the performance of the two systems for a range of PCSM.

3.1 The emergy input structure

The relative rankings of the two systems are different according to the indicators considered (Fig 3). The total emergy input (U) to support the SCS and ICLS is 9.36E+15 sej·ha^{-1}·yr^{-1} and 1.79E+16 sej·ha^{-1}·yr^{-1}, respectively (Fig. 3a). The purchased resources input of the ICLS is 1.58E + 16 sej·ha^{-1}·yr^{-1}, which is 2.70 higher than that of SCS (Fig. 3b). These results show that ICLS consumes more total emergy input and purchased emergy input than the SCS; therefore, ICLS requires more emergy to operate the whole system.

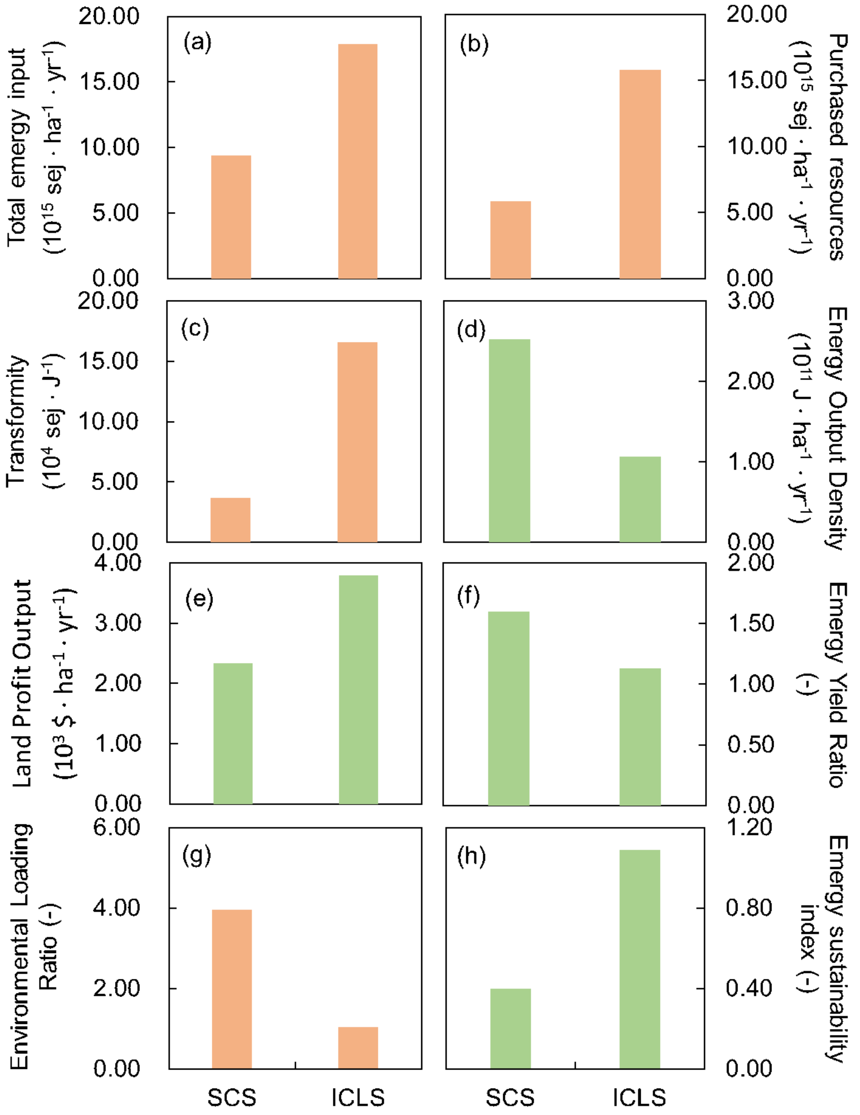

Fig. 3 The indicators of emergy resources utilisation (a ~ b), productivity (c ~ f), environmental pressure (g), and sustainability (h) of an average SCS and an ICLS. In detail, the panels represent the following: (a) total emergy input (U), (b) purchased resources (F), (c) transformity (Tr), (d) energy output density (EOD), (e) land profit output (LPO), (f) emergy yield ratio (EYR), (g) environmental loading ratio (ELR), and (h) emergy sustainability index (ESI). The red bars represent costs (the lower the indicator, the better for the paradigm, i.e., Fig. a, b, c, and g). The

green bars represent benefits (the higher the indicator, the better for the paradigm, i.e., Fig. d, e, f, and h).

3.2 The productivity

The productivity of the SCS was higher than that of the ICLS in terms of system efficiency, land energy production, and emergy return on emergy investing, while the productivity of the ICLS was higher from the viewpoint of land economic benefit output. Fig. 3c shows that the transformity of the ICLS is (Tr_{ICLS}= 1.66E+05 sej·J^{-1}) greater than that of the SCS (Tr_{SCS}= 3.71E+04 sej·J^{-1}), which indicates that the ICLS requires more emergy input than the SCS when producing the same amount of energy. Fig. 3d shows that the energy output density of ICLS (EOD_{ICLS} = 1.07E+11 J·ha^{-1}·yr^{-1}) is lower than that of the SCS (EOD_{SCS}= 2.52E+11 J·ha^{-1}·yr^{-1}), which indicates that ICLS requires more land than the SCS when producing the same quantity of energy. Fig. 3e shows that the land profit output of the ICLS (LPO_{ICLS} = 3789.94 \$·ha^{-1}·yr^{-1}) is higher than that of the SCS (LPO_{SCS} = 2339.61 \$·ha^{-1}·yr^{-1}), which indicates that ICLS offers higher economic benefits than SCS in the same area of land. Fig. 3f shows that the emergy yield ratio of the SCS and the ICLS are 1.60 and 1.13, respectively, which indicates that the ICLS has a lower emergy return on emergy investing and a lower ability to utilise local resources by investing externally procured resources.

3.3 The environmental pressure and emergy sustainability

Fig. 3g shows that the environmental loading ratio of the SCS is 3.96, which is approximately 3.8 times that of the ICLS (ELR_{ICLS} = 1.04), indicating that the agricultural production of SCS puts higher pressure on the environment than that of ICLS. Fig. 3h shows that the emergy sustainability indexes of ICLS and SCS are 1.09 and 0.40, respectively, indicating that ICLS has higher emergy sustainability than SCS.

3.4 Performance of ICLS and SCS under variation of manure fertiliser application

We analysed the performance of productivity (T_r, EYR), environmental pressure (ELR), and emergy sustainability (ESI) with the change in PCSM for the ICLS and the SCS (Fig. 4). For all these indicators, the SCS showed continuous changes with the PCSM, as manure was considered an imported resource for PCSM > 0; on the contrary, the ICLS showed a different trend below and above 52% PCSM, as below that value, locally available manure was used, whereas, above that value, imported manure was used. The behaviour of the two systems was different, and their relative performances were different along the PCSM gradient.

Concerning transformity, Fig. 4a shows that for ICLS, the indicator decreases slightly and reaches its lowest value for 52% PCSM and then increases linearly with the PCSM, showing that the system production efficiency increases and then decreases. In the SCS, the transformity increases linearly with an increasing PCSM, indicating that the system production efficiency decreases linearly with increasing amounts of manure fertiliser and is highest when utilizing chemical fertiliser. For the same PCSM, and when the PCSM was greater than ～35%, the transformity of the ICLS is lower than that of the SCS, indicating that, starting from that point, using local manure is more efficient than importing it.

Concerning the emergy yield ratio, Fig. 4b shows that in both systems, the indicator starts to decrease when manure is a purchased resource. For the SCS, the indicator decreases with the PCSM, whereas for the ICLS, the indicator increases slightly until ～52% PCSM and then decreases. When the PCSM ≥19%, the emergy yield ratio of the ICLS is greater than that of the SCS, indicating that for those values of the PCSM, the emergy return on emergy investment is higher using local manure.

Concerning the environmental loading ratio, for the ICLS, the indicator decreases linearly until

~52% PCSM, and then decreases curvilinearly with the PCSM; for the SCS, the indicator decreases drastically with increasing PCSM. For PCSM values starting from ~9%, the imported manure for SCS has a lower environmental loading ratio than that for ICLS. Indeed, ICLS has other non-renewable resource inputs (especially for the greenhouse and livestock sectors) that keep the environmental loading ratio higher than the crop-only system with organic manure (Supplementary Table S3).

Concerning emergy sustainability, for the ICLS, the indicator increases linearly first and then curvilinearly for PCSM values greater than ~52%. For the SCS, the emergy sustainability increases curvilinearly with the PCSM. For PCSM values greater than ~7%, the emergy sustainability of the ICLS is lower than that of the SCS due to the lower environmental loading ratio of SCS.

Fig. 4 also shows that trade-offs, i.e., the increased use of organic manure over organic fertiliser, lead to a lower environmental loading ratio and increased emergy sustainability and a lower efficiency and lower emergy yield ratio. Trade-offs are also present in the preferability of the ICLS over the SCS: for low values of manure use (close to 0%), the SCS is preferable to the ICLS for transformity and emergy yield ratio, but not for environmental loading ratio and emergy sustainability. Thus, a system that relies on synthetic fertiliser is more efficient but impacts the environment more than a system relying on its manure. For high values of manure use (close to 100%), the SCS performs better than the ICLS on environmental loading ratio and emergy sustainability but less than the SCS on transformity and emergy yield ratio. In the range of 0–100%, the trade-off changed because the relative performance of the two systems switched at different thresholds for the different indicators.

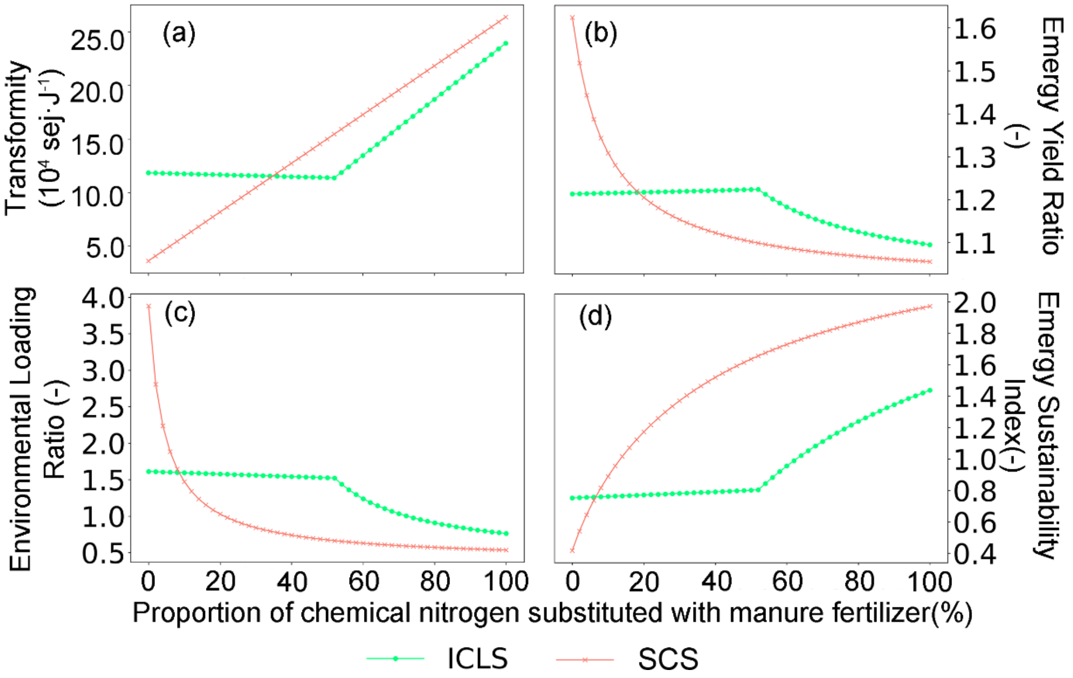

Fig. 4 The performance of productivity, environmental pressure, and emergy sustainability for average SCS and ICLS with the change of chemical nitrogen substituted with manure fertiliser. The green line represents the performance of ICLS and the red line shows the performance of SCS. In detail, panels represent the following indicators: (a) transformity (Tr), (b) emergy yield ratio (EYR), (c) environmental loading ratio (ELR), and (d) emergy sustainability index (ESI). The PCSM values in practical SCS and ICLS are 0% and 70%, respectively.

4. Discussion

In this study, we assessed the system performance of one modern ICLS and one typical SCS using eight indicators and simulated the performance of some of these indicators under a gradient of increasing manure-use fraction in total nitrogen need. We found that the performance in terms of resource utilisation, productivity, environmental pressure, and sustainability was different between the ICLS and the SCS. In addition, under the conditions of constant total nitrogen need, the performance differed between the ICLS and the SCS with increasing manure use.

4.1 Comparing SCS and ICLS

Analysing the performances of the two systems on multiple dimensions helped to highlight the strengths and weaknesses of each system. The SCS has considerable productivity (T_r = 3.71E+04 sej·J^{-1}; EOD = 2.52E+11 J·ha^{-1} · yr^{-1}; EYR = 1.60). This is very common for these types of systems, which usually depend on cultivation techniques and the use of machinery, chemical fertilisers, and pesticides (Moraine et al., 2017). Almost all farming procedures in SCS, including soil preparation, sowing, and harvesting, can be done by machinery, which sharply improves agricultural labour productivity (Baležentis et al., 2020; Liu, S. et al., 2018). The use of abundant nutrients, such as chemical nitrogen, phosphorus, and potassium fertilisers, allows for more direct control and precision in the delivery of nutrients that would maintain soil fertility levels for supporting higher yields (Cabrera and Solis-Perez, 2017). However, this comes at the expense of environmental resources, as the long-term application of chemical fertiliser would destroy soil structure, and may also cause soil acidification and water pollution (Wallace, 1994). In addition, according to Yan et al. (2014), China has a low nitrogen use efficiency of 30–35%, compared to 52% in America and 68% in Europe, due to widespread overuse of chemical fertilisers (Meng et al., 2016). More industrial and non-renewable resource inputs (mostly groundwater, synthetic nitrogen, and phosphate) of the SCS led to greater pressure on the environment (ELR = 3.96), and the non-renewable resource input caused weak sustainability in terms of resource utilisation. This leads to a weak emergy sustainability (ESI = 0.40).

The ICLS was designed to solve environmental pressure and maintain productivity compared to SCS. The proportion of renewable resource input of the ICLS was higher than that of the SCS at the system level, leading to lower pressure on the environment (ELR = 1.04). The ICLS had a higher land profit output, mainly owing to the contribution of livestock and vegetables. The economic value of livestock and vegetables is higher than that of crops, as reflected by their net economic benefits (PNRC, 2018). According to the PNRC (2018), the average net profit per 50 kg of wheat, maize, vegetables, eggs, and meat are 0.70 Yuan, -16.98 Yuan, 28.46 Yuan, 18.92 Yuan, and -13.85 Yuan, respectively. Livestock requires only a small land area and is not affected by soil quality (Ryschawy et al., 2017). In addition, the emergy sustainability of the ICLS (ESI = 1.09) was higher than that of the SCS at the system level. However, EOD and EYR in the ICLS were lower than in the SCS, and T_r in the ICLS was higher than in the SCS, indicating a lower productivity of land energy output efficiency, emergy return on emergy investment, and production efficiency in ICLS, respectively. This may be caused by the non-optimal design of the crop-livestock structure, which is a critical factor for ICLS (Sneessens et al., 2016). The ICLS adopts the principles of a circular economy that reduce, reuse, and recycle materials, which is a sustainable development strategy (Heshmati, 2017). These principles are important for achieving a better performance of ICLS when designing each subsystem (e.g., crops and livestock).

4.2 Increasing the usage of organic manure

Increasing the use of manure in crop cultivation is recommended to improve sustainability. The overuse of synthetic fertilisers may also threaten human health and cause serious environmental problems (Ahmed et al., 2017). The results showed that increasing the fraction of fertiliser coming from organic manure brings a trade-off: while the environmental pressure decreases, productivity decreases. The reason for decreased productivity is that the total nitrogen input was constant while PCSM increased; the organic matter from the manure was an additional input resource for the ICLS and SCS, which caused an increase in the purchased resources input. In the scenario of an increasing PCSM, we assumed that agricultural products did not change. Therefore, the system production efficiency (T_r) and emergy return on emergy investment (EYR) decreased. The decrease in environmental pressure was due to the increase in renewable resource input and decrease in non-renewable resource input when the chemical nitrogen was substituted with manure fertiliser.

The two systems reacted differently to the increase in fertiliser input. For the SCS, manure was considered an imported resource. Along with the range of the PCSM from 0–100%, there were drastic changes in the indicators: if the environmental performance substantially improved (decrease in environmental loading ratio and increase in emergy sustainability), the productivity performance substantially worsened (increase in transformity and decrease in emergy yield ratio). For the ICLS, manure was, to some extent, an internally recycled resource and only partially an imported resource. For such systems, the trend in the indicators was similar but with two important differences: the indicators changed weakly until a threshold corresponding to the availability of manure in the system was reached. When manure had to be imported (i.e., the need was greater than the internal availability), the indicators changed (the environmental indicators improved and the productivity indicators decreased). However, along the PCSM gradient, the trade-off between productivity and environmental indicators was more gradual with respect to the ICLS, that is, the productivity increased and environmental pressure decreased before the manure was imported, and the difference in indicator performance between PCSM = 0% and PCSM = 100% was lower than that of the SCS. This highlights the buffering role of livestock (Ryschawy et al., 2012).

It should be noted that for very high values of PCSM, the environmental performance of the SCS is better than that of the ICLS, meaning that imported manure in a crop-only system seems more sustainable than a crop-livestock system using the same quantity of manure, both local and imported. This higher environmental pressure in the ICLS compared to the SCS for high PCSM is due to the presence of livestock and greenhouses on the farm. For example, compared to crops (i.e., wheat and maize), livestock and greenhouses (i.e., vegetables) consume more non-renewable resources, such as electricity and plastics. These might create more adverse environmental impacts while guaranteeing a better level of manure availability and economic benefits of ICLS compared to SCS.

4.3 The promising paradigm of integrating crops and livestock

Lemaire et al. (2014) pointed out that the trade-off between the necessity to improve productivity for food security and to reduce environmental risk factors must be overcome in the agricultural paradigm. Our analysis showed that trade-offs are present in the choice of ICLS over SCS. Fig. 4 shows that the SCS performs better than the ICLS with a PCSM value of approximately 19% according to the emergy indices (T_r, EYR, ELR, and ESI), which is also one of the potential temporary solutions to solve manure pollution and maintain productivity. In addition, labour productivity, defined as the yield (Y) divided by the labour input (L) of the SCS (2.91E-04 J·sej^{-1}), is higher than that of the ICLS (6.13E-05 J·sej^{-1}) (the data of L and Y refer to Supplementary Tables S2 and S3). However, some arguments remain in favour of ICLS. As an experimental paradigm, the ICLS was designed to achieve the recycling of resources, which reduces the dependence on external resources to a certain extent and can reduce production costs and risks of market fluctuations (Ryschawy et al., 2017). All the forage grains produced by the crop production subsystem are used for the livestock subsystem, and all the manure produced by the livestock subsystem is used for crop production and vegetable subsystems within the whole ICLS (Herrero et al., 2010). As a renewable resource, manure fertiliser is the main nutrient for crops and vegetables in the ICLS, which reduces the dependence on non-renewable resources and improves the sustainability of resource utilisation. In the future, agricultural production systems should perform well with lower chemical nitrogen input but higher manure nitrogen input. The SCS systems performed well at 20% and could be temporarily beneficial in a transition from the current systems to an organic system. However, 20% of manure nitrogen use means very high usage of chemical nitrogen, which should be avoided in the future. To scale up systems in which an increasing amount of manure fertiliser is used, it is important to change the system configuration (switching from SCS to ICLS) and further optimise the ICLS.

Overuse of synthetic fertiliser leads to environmental pollution (Chen et al., 2014). In addition, in the eastern regions of China, there is a distinct separation among intensive livestock systems (often close to peri-urban areas), hotspots of nitrogen and phosphorous accumulation (Li et al., 2008). Increasing the fraction of organic manure in crop fertilization practices is an important strategy for reducing the environmental impacts of China's agriculture. Our results showed that if manure is directly available on the farm, it can contain the environmental impacts of agriculture and maintain a high level of productivity. For ICLS (taking the Beiqiu Farm as an example), the productivity (T_r and EYR) increases slightly and the environmental pressure decreases slightly when the PCSM is less than 52%, which alleviates the trade-off between decreasing productivity and decreasing environmental pressure. This is mainly because manure can be supplied by the internal livestock subsystem—where manure fertiliser need not be imported when less than 52% chemical nitrogen substitution. Further optimization of the ICLS can make the system more self-sufficient in terms of manure; in other words, ICLS can be optimised so that livestock would provide manure for the crops, which would decrease GHG emissions by reducing transportation (Pradhan et al., 2020).

As one of the promising future crop-livestock systems, there is a trade-off relationship between productivity (e.g., T_r and EYR) and environmental cost (e.g., ELR) for agricultural production. This is consistent with other findings in the literature, for example, Wu et al. (2015b) found that the values of T_r EYR, and ELR of an ICLS were 7.13E+04 sej·J^{-1}, 1.54, and 3.19 in Yijun County of Tongchuan City, Shaanxi Province, China, which indicate higher productivity and higher environmental pressure compared to the experimental ICLS (i.e. Beiqiu Farm) (T_r = 1.66E+05 sej·J^{-1}, EYR = 1.13, ELR = 1.04). The environmental pressure of agricultural production in the future calls for softer trade-off related to ICLS, that is, increasing productivity without increasing environmental pressure. The productivity of experimental ICLS must be improved compared to SCS (T_r = 3.71E+04 sej · J^{-1}, EYR = 1.60), while maintaining lower environmental pressure through several policy measures (i.e., reducing external input and increasing production per unit area of arable land). To reduce external input, optimization of crop-livestock balance can reduce the manure fertiliser input and might also contribute to reducing feed-food competition. In addition, the labour productivity of ICLS can be improved by adopting intelligent and automated agricultural machinery in the future (Li et al., 2018), and there is a positive correlation between crop production and machinery power input (Li et al., 2021). Furthermore, the scientific application of water and fertiliser for crops can also reduce the input of external resources. To increase production per unit area of arable land, the productivity of ICLS must be improved through engineering and cultivated technologies, such as planting crop varieties with a high yield and strong resistance to adversity (e.g., high wind, diseases, and insect pests). The development of scientific-release organic fertiliser and research on the scientific application of manure fertiliser (Xiang et al., 2008), which can improve nutrient absorption in crops, requires increased funding from the government. To improve productivity effectively through the two main types of policy measures, farm managers need further training on the agronomy of crops, vegetables, livestock, and other agricultural systems, and the correlation between each subsystem due to the complexity of ICLS (Ryschawy et al., 2012). The professional training of farmers (Zhao et al., 2019) should be promoted by the government. Considering the advantages of ecological utilisation of manure, system stability, the sustainability of resource utilisation, and higher economic benefit, the ICLS paradigm could be a choice for China for future agricultural production in regions with serious manure pollution and cultivated land degradation (Wu et al., 2013; Ryschawy et al., 2017).

5. Conclusion

This study compared two agricultural paradigms, the most widely used SCS and the more innovative ICLS, to propose suggestions to improve the performance of the latter. Compared to the SCS, the ICLS puts less pressure on the environment, has higher emergy sustainability, and higher economic benefits per unit land area but consumes more emergy input and has lower productivity.

Facing huge livestock product demand with income growth, population growth, and urbanization (Thornton, 2010), and greater livestock manure production in the future, China must pay attention to livestock manure management by integrating livestock and cropping systems. If the use of manure is encouraged over synthetic fertiliser, ICLS can alleviate the trade-off between decreasing productivity and decreasing environmental pressure with internal resource recycling. On the contrary, there was a sharp trade-off between system production efficiency and environmental pressure in the SCS, in which the productivity and environmental pressure decreased sharply with increasing PCSM.

Considering the several benefits of sustainable resource utilisation, environmentally friendly production, and system stability, the ICLS could be an alternative future agricultural production system in regions with serious manure pollution and cultivated land degradation. However, further research and innovation are needed to improve ICLS. Within the ICLS, there is a need to optimise the crop-livestock structure, strengthen scientific management, and improve productivity. In addition, farmers must be trained in the agronomy of crop-livestock during ICLS promotion in China.

Declaration of competing interest

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

CRediT authorship contribution statement

Yang Li: Methodology, Investigation, Formal analysis, Data curation, Writing - original draft, Visualization. **Zhigang Sun:** Conceptualization, Supervision. **Francesco Accatino:** Writing-Reviewing and Editing, Supervision. **Sheng Hang:** Methodology. **Yun Lv:** Methodology. **Zhu Ouyang:** Supervision.

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Appendix A. Supplementary material

Supplementary data related to this article can be found online.

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