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# Sustainability Evaluation of the Maize–Soybean Intercropping System and Maize Monocropping System in the North China Plain Based on Field Experiments

**Xiaolei Yang [1], Peng Sui [1], Yawen Shen [1], James S. Gerber [2], Dong Wang [1], Xiaolong Wang [3], Hongcui Dai [4] and Yuanquan Chen [1,*]**

1 College of Agronomy, China Agricultural University, Beijing 100193, China; yang6651@umn.edu (X.Y.); suipeng@cau.edu.cn (P.S.); shenyawen1988@cau.edu.cn (Y.S.); wangdong_1995@163.com (D.W.)
2 Institute on the Environment, University of Minnesota, St. Paul, MN 55108, USA; jsgerber@umn.edu
3 College of Agronomy, South China Agricultural University, Guangzhou 510642, China; wangxiaolong@scau.edu.cn
4 Crop Research Institute, Shandong Academy of Agricultural Sciences, Jinan 250100, China; daihongcui2013@163.com
* Correspondence: rardc@163.com; Tel.: +86-10-62731163

Received: 20 September 2018; Accepted: 12 November 2018; Published: 19 November 2018

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**Abstract:** Monocropping systems, which currently dominate China's major grain production regions, contribute to resource scarcity and environmental pollution. Intercropping has the potential to improve resource use efficiency. However, prior studies of intercropping systems have generally focused on ecological, economic, and social consequences. Here, we make a comparative ecological sustainability analysis on energy capture and efficiency of maize monocropping and maize–soybean intercropping systems through emergy evaluation based on field experiments performed from 2012 to 2014. We find that maize monocropping shows higher sustainability than maize–soybean intercropping in the North China Plain at present. Quantitative results indicate that for maize monocropping, the emergy yield ratio (EYR) and emergy sustainability index (ESI) are 13.7% and 21.1% higher than that of intercropping systems, and the environmental loading ratio (ELR) is 7.3% lower than that of intercropping systems. To further test, we applied three levels of nitrogen fertilizer in intercropping systems (120 kg ha$^{-1}$, 180 kg ha$^{-1}$, 240 kg ha$^{-1}$), and find that a reduced rate of N fertilizer for intercropped system leads to higher sustainability (ESI 5.3% higher) but still lower sustainability than maize monocropping. Key drivers of the different sustainability outcomes are decreased energy output and a larger proportion of labor input associated with intercropping systems.

**Keywords:** emergy; maize monocropping; maize–soybean intercropping; sustainability; the North China Plain

## 1. Introduction

Increased crop demand by a growing population and changing diets poses a variety of sustainability challenges to the global agricultural system [1,2], including food insecurity [3], accompanied by scarcity of natural resources [4,5], pollution of ground water [6], excessive application of chemical fertilizer [7], substantial losses of biodiversity [8] and climate change [9], which are ongoing issues. Agricultural practices determine the level of food production, even the state of the global environment [2].

These global scale issues play out within China as well. In response to domestic demand and government policies, China's agricultural sector has nearly doubled grain production from 1980 to

2016. Such achievements in grain production have resulted in considerable environmental problems domestically and abroad [10].

The North China Plain (NCP) is one of the major grain production areas in China, with 35 million ha of croplands, and the wheat–maize double cropping rotation dominant over 14 million ha [11,12]. It is also the major maize production area in China; 35% of the country's maize is produced on almost 8 million ha of arable land in the North China Plain [13]. Since the 1950s, the main type of cropping system in the NCP has changed from single-cropping to wheat–maize double cropping system [14]. With changes in cropping systems, a notable increase in yields over the last three decades came at the cost of high consumption of nonrenewable resources and environmental degradation [15,16]. At present, there exist more serious water resource shortages and environmental degradation in the NCP than other main grain production areas in China. For instance, underground water tables are declining at a rate of up to one meter annually throughout the north China aquifer [17]. Utilization rate of chemical fertilizer increased from 100 to 600 kg $ha^{-1}$ per year for the past two decades [18]. Agriculture is the major source of greenhouse gas (GHG) emissions and discharges 6432.3–6527.3 kg $CO_2$-eq $ha^{-1}$ $yr^{-1}$ from the entire growing season in the NCP [19]. It is imperative to develop more sustainable agricultural practices to increase resource use efficiency and reduce environmental impacts on agricultural systems [1,3].

Previous research has reported that intercropping makes better use of resource and achieves higher productivity for facilitation, resource sharing and niche complementarity [20], yield and nutrient uptake advantage [21], higher radiation capturing and utilization efficiency for vertical distribution [22] and achieves higher water productivity due to an increase in water capture efficiency [23]. Furthermore, intercropping systems are favored to enhance the radiation use efficiency (RUE) when compared to their monocropped counterparts [23,24]. Due to low profits from soybean production [13], maize–soybean intercropping is less common in the North China Plain, where around 11.7% of cultivated land is under soybean production [25]. However, because of the strengths researchers found in cereal–legume intercropping on the premise of ensuring the maize production, it has been proposed that developing maize–soybean intercropping would be beneficial in the North China Plain to improve the ecological function of the maize production area [13]. In China, maize production has increased by 39.4% while soybean area declined by 24.9% in China since 2005 [26]. Therefore, this paper focuses on the comparison between maize monocropping and maize–soybean intercropping. Researchers have done many studies using various methods to examine the intercropping systems. Adeniyi (2001) [27] applied economic indicators to evaluate the tomato–okra intercropping. Koocheki et al. (2016) [28] analyzed the yield, quality, and total land equivalent ratio on different row arrangements in saffron–cumin intercrops. Himmelstein et al. (2017) [29] applied meta-analysis to determine the impacts of intercropping systems on crop yield, land equivalent ratio (LER), gross income and concurrent management factors. Martin-Guay et al. (2018) [30] determined the merits of intercrops from the perspectives of energetic, economic, and land-sparing potential. Most literature focused on the benefits of cereal–legume intercropping. Pelzer et al. (2012) [31] stated that pea–wheat intercrops could maintain wheat grain protein concentration, increase the contribution of $N_2$ fixation, and decrease pesticide use and soil mineral nitrogen after harvest. Xiong et al. (2013) [32] used a proteomic approach to analyze the ecological performance of peanut–maize intercrops from the molecular angle. Naudin et al. (2014) [33] demonstrated that pea–wheat intercrops have lower environmental impact than monocrops based on life cycle assessment (LCA). Huang et al. (2017) [34] reported that maize intercropping with soybean has the advantage of reducing soil $N_2O$ emission relative to maize monoculture. In general, previous studies comparing monocropping and intercropping systems have generally been researched using various methods on ecological, economic, or social consequences, while research on ecological sustainability of maize–soybean intercrops from the energy input–output and efficiency is still lacking.

In recent years, the emergy method, originally introduced in the 1980s by H.T. Odum (1996) [35] and defined as the sum of the available energy of one kind previously required directly and indirectly through input pathways to make a product or service [36], then gained widespread use for quantitative assessment on environmental sustainability and economic accounting. The emergy method offers a "donor-side" perspective to involve "free" environmental resources, information, and human services to uncover the ecological consequences and to maximize the resource efficiency [37]. The emergy method creatively addresses the shortcomings of traditional energetics by relating different forms of energy through a common physical basis, solar emergy, which is used to analyze the compound system at the interface between the "natural resources" and "human systems" [38]. Therefore, emergy works comes to be a suitable method to address the agroecosystem [14,39–42]. Emergy synthesis provides a comprehensive analysis of the environmental performances of cropping systems. Analysis of the sustainability of agricultural systems is particularly complex. Such an analysis has to contend with spatial heterogeneity due to agrometeorological factors, and the differing impacts on both resource inputs and crop outputs of various cropping systems. Emergy analysis is well suited to handle this complexity. Therefore, this study takes the data from 3 years of field experiments and applies emergy analysis to evaluate environmental consequences and sustainability on maize–soybean intercropping systems compared to maize monocropping systems.

## 2. Materials and Methods

### 2.1. Experimental Site and Design

Field experiments were conducted at the Wuqiao experiment station of China Agricultural University in Cangzhou which is located in Hebei province of the North China Plain. This region is characterized with a temperate semiarid monsoon climate. The geographic position is 116°37′ E and 37°41′ N. The average annual rainfall was 562 mm and most concentrated during June to August. The main cropping pattern in this region is a winter wheat–summer maize rotation system. The experiments were conducted from 2012 to 2014, the area management before the experiments was a long-term wheat–maize rotation. Treatments included maize (*Zea mays* cv. Zhengdan 958) monocropping (M) and 2-row maize (60 cm row spacing) with 2-row soybean (*Glycine max* cv. Zhonghuang 13, 40 cm row spacing) intercropping (MS), the distance between adjacent maize and soybean rows was 40 cm. In addition, the niche complementarity between the cereal (that uptake N from soil) and the legume (that fix N from $N_2$ in the atmosphere) increases N capture and use efficiency [20,43]. According to the lower N fertilization that maize–legume intercropping systems need, treatment with 120 kg ha$^{-1}$ (MS120) and 180 kg ha$^{-1}$ (MS180) on maize–soybean intercropping systems were conducted for further analysis. In June 2012, four treatments were established at the site in a randomized block design with three blocks, for a total of 12 experimental plots. According to the emergy concept and methodology that Odum (1996) [35] provided, energy sources (shown in Figure 1) driving the farming management are all included in emergy analysis, which summarizes the system boundaries for cropping system based on the duration from sowing to harvesting.

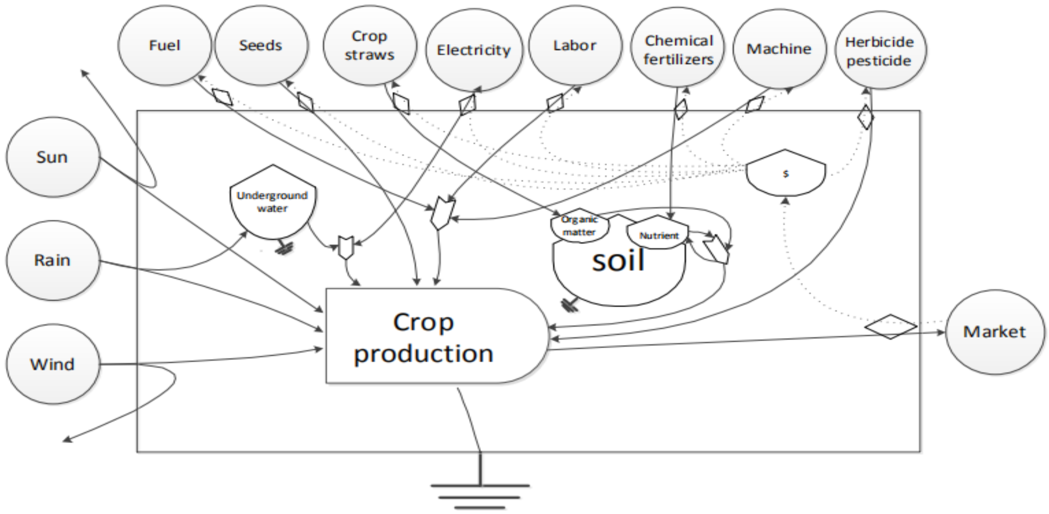


**Figure 1.** Energy flow diagram of the cropping system. ⬭ means a compartment of energy storage; ⬭ represents source of energy; ▭ means producer; → is the flow of material; ······ is the flow of money.

## 2.2. Raw Data Sources

In this study, raw data were collected from the field experiments during 2012 to 2014. The input and output of four treatments were collected from the average value of all plots in 3 years. The lifespans of agricultural machines were collected from the owners and then calculated to annual flows. As collected and recorded, maize in monocropping treatments was sown at densities of $6.67 \times 10^4$ seedlings per hectare with application of 75 g ha$^{-1}$ effective ingredient of herbicide and pesticide. In the maize–soybean intercropping system, maize was sowed at $4.44 \times 10^4$ and soybean at $1.31 \times 10^5$ seeds per hectare, respectively. The effective ingredient of pesticide application rate was applied at 39.33 g ha$^{-1}$ for the intercropping system. In maize monocropping, pesticide (Coragen) and herbicide (Nicosulfuron) were applied in huge bellbottom stage. While in maize–soybean intercropping, pesticide (Coragen) for maize was applied in huge bellbottom stage, Imidacloprid and Beta-cyfluthrin for soybean applied in beginning bloom period and pod filling stage respectively. Crops were sown on 15 June 2012, 18 June 2013, and 18 June 2014, then, maize and soybean were harvested on 1 October 2012, 2 October 2013, and 2 October 2014. The average growth periods of M and MS treatments were 106 days, 75 mm irrigation water was applied to all plots on the soil surface and 750 kWh ha$^{-1}$ of electricity consumption. Before planting, plots were fertilized with calcium superphosphate (75 kg $P_2O_5$ ha$^{-1}$) and potassium sulphate (90 kg $K_2O$ ha$^{-1}$), which was broadcast and incorporated in solid form (15 cm depth). Farmers in the North China Plain apply relatively high rates of N fertilizer to maize, and frequently apply N fertilizer to soybean [26]. A total of 240 kg N ha$^{-1}$ fertilizer was applied in two applications which occurred either after rainfall or prior to irrigation. The fuel consumption of both systems was 47.25 kg ha$^{-1}$. In terms of experiment management, in both cropping systems, single-spray irrigation was conducted after mechanical sowing. Maize and soybean were harvested by machine and labor, respectively. More details are shown in Table 1. In addition, this case established three N application rates on intercropping systems without change to agronomic management to assess the sustainability and resources utilization rate of cropping systems. The three levels of N application rate are, respectively, 120 kg ha$^{-1}$ (MS120), 180 kg ha$^{-1}$ (MS180), 240 kg ha$^{-1}$ (MS).

**Table 1.** The inputs/outputs of the cropping systems ($ha^{-1}$).

| Item | Sowing | Growth | Harvesting |
|---|---|---|---|
| Groundwater ($m^3$) for irrigation | / | 750.38 | / |
| Fuel (kg) | 12.75 | / | 34.50 |
| Machine (g) | 20,625.00 | / | 37,500.00 |
| Labor (M) (Work day) | 0.47 | 10.94 | 0.47 |
| Labor (MS) (Work day) | 0.47 | 64.26 | 12.97 |
| Herbicide (M) (g) | / | 60.00 | / |
| Pesticide (M) (g) | / | 15.00 | / |
| Herbicide (MS) (g) | / | / | / |
| Pesticide (MS) (g) | / | 39.33 | / |
| Electricity (kwh) | / | 750.00 | / |
| Seeds (M) (kg) | 27.27 | / | / |
| Seeds (MS) (kg) | 44.19 | / | / |
| N (kg) | / | 240.00 | / |
| $P_2O_5$ (kg) | 75.00 | / | / |
| $K_2O$ (kg) | 90.00 | / | / |
| Maize yield (M) (kg) | / | / | 9103.00 |
| Maize yield (MS) (kg) | / | / | 6822.00 |
| Soybean yield (MS) (kg) | | | 527.00 |

Note: M represents maize monocropping system; MS represents maize–soybean intercropping system; The input of machine was calculated by the ratio of total machine weight to lifespan and annual working area; work time per day is 8 h.

Emergy evaluation is a broad theory introduced by Odum on the functioning of ecosystems [35]. The fundamental parameter solar emergy, which is usually measured in solar emergy joules (sej), allows different qualities and quantities of energy to be compared through solar transformity (sej/J) [44]. Solar transformity (sej/J) refers to the solar emergy required to generate a J of product or service [35].

### 2.2.1. Emergy Accounting

The first step is to identify the classification and relationships among emergy input. For the current study, for tracing back to the original inputs of purchased goods, labor and services, we divide emergy input into renewable and nonrenewable parts through renewability factor (RNF), which improves the accuracy and rationality of the evaluation results [39,45]. The classification and partition was discussed in detail by Ortega et al. (2002) [46], Cavalett et al. (2006) [47] and Castellini et al. (2006) [38]. In this study, energy inputs are classified into feedback from the economy or purchased resources (F) and natural environmental resources (E), and each item is analyzed through RNF. The second step is to build the emergy table of each input or output flow mentioned in energy diagrams (Table 4). The data of annual average sunlight and wind are taken from the China Meteorological Data Sharing Service System. Rainfall data are obtained from Wuqiao experimental station. Energy coefficients used to calculate the energy content of fuel, labor, seed, electricity, output energy of maize and soybean are all taken from Chen (2011) [48]. Then, the emergy of input and output are calculated by multiplying by relevant solar transformities, which in this case were based on the 15.83E+24 sej/year standard [49] and formulas are provided by Odum (1996) [35]. In the emergy evaluation, among the solar, rain, and wind emergy input, rain and wind are regarded as coproducts of sun, it is only to calculate the largest emergy value of three items for avoiding the repetitive computation [35]. All unit emergy values (UEV) and renewability factors (RNF) applied in this article are listed in Table 2.

**Table 2.** UEV and RNF applied in this study.

| Item | UEV | Reference | RNF | Reference |
|---|---|---|---|---|
| Sun | 1.00E+00 | Odum (1996) [35] | 1.00 | Odum (1996) [35] |
| Wind | 2.45E+03 | Odum et al. (2000) [49] | 1.00 | Odum (1996) [35] |
| Rain | 3.10E+04 | Odum et al. (2000) [49] | 1.00 | Odum (1996) [35] |
| Underground water | 2.45E+05 | Buenfil (2001) [50] | 0.10 | Sun et al. (2006) [51] |
| Soil | 1.24E+05 | Brandt-Williams (2002) [52] | 1.00 | Odum (1996) [35] |
| Fuel | 1.11E+05 | Odum et al. (2000) [49] | 0.00 | Zhang et al. (2011) [53] |
| Machine | 1.13E+10 | Brown and Ulgiati (2002) [54] | 0.00 | Zhang et al. (2011) [53] |
| Labor | 7.56E+06 | Brandt-Williams (2002) [51] | 0.12 | Wang (2016) [55] |
| N | 6.38E+09 | Odum (1996) [35] | 0.00 | Odum (1996) [35] |
| $P_2O_5$ | 6.55E+09 | Odum (1996) [35] | 0.00 | Odum (1996) [35] |
| $K_2O$ | 1.85E+09 | Odum (1996) [35] | 0.00 | Odum (1996) [35] |
| Herbicide and pesticide | 2.49E+10 | Odum (1996) [35] | 0.00 | Odum (1996) [35] |
| Seeds | 1.11E+05 | Odum (1996) [35] | 1.00 | Castellini et al. (2006) [38] |
| Electricity | 2.87E+05 | Brown and Ulgiati (2002) [54] | 0.09 | Brown and Ulgiati (2002) [54] |

Note: UEV refers to unit emergy value; RNF refers to renewability factor.

### 2.2.2. Soil Emergy Input

An agroecosystem is a semi-natural and semi-artificial system, soil is a complex, changing, and dynamic component, which is influenced by agronomic activities. Practically, the soil organic matter fluctuates during years and has variations between maize monocropping and maize–soybean intercropping from the experimental data. While previous research analyzed the soil input between systems through same soil organic matter for systematic calculation [56], this paper aims to refine the physiological differences between two cropping system. Soil samples were collected during harvesting period (around the beginning of October) to estimate soil organic matter. The difference of soil organic matter between maize monoculture and maize–soybean intercropping is analyzed by *T* test. As showed in Figure 2, that soil organic matter content in maize monoculture is slightly different with intercropping though there is no significant difference between the two treatments ($P > 0.05$), which may lead to 0.9% decrease of soil emergy input in intercropping system. As to intercropping treatments on a multiple nitrogen fertilizer level, soil organic matter is also calculated into the energy of soil loss.

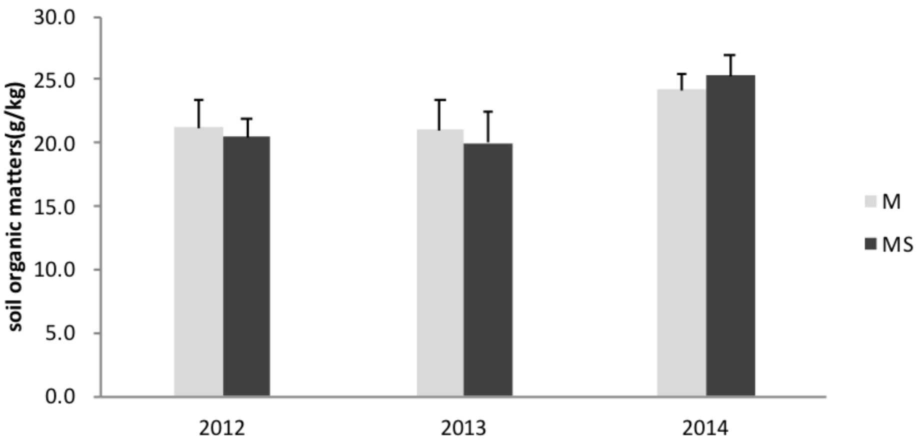


**Figure 2.** Soil organic matter change of two cropping systems. Values are means ± standard deviation. M is maize monocropping system, and MS is for maize–soybean intercropping system.

The formula of the energy of soil loss obtained from Hu et al. (2010) [56]:

$$E_S = y_s \times m \times e_s \times c, \quad (1)$$

where the $E_s$ is the energy of soil loss; $y_s$ is the average soil loss (t ha$^{-1}$); $m$ is organic matter (g/g); $e_s$ is soil organic matter energy (kcal/kg); $c$ is conversion (J/kcal).

### 2.2.3. Emergy Indices

Five emergy-based indices listed in Table 3 are used to calculate and evaluate the environmental performance of the cropping systems.

**Table 3.** Expression and description of emergy indices.

| Emergy Indices | Units | Expression | Description |
|---|---|---|---|
| Unit Emergy Value (UEV) | sej/j | Y/$E_Y$ | It represents how much emergy input is required to produce a unit of output and measures the resources utilization rate of production system |
| Unit Nonrenewable Value (UNV) | sej/j | N/$E_Y$ | It measures the nonrenewable resources utilization rate for a unit output |
| Emergy Yield Ratio (EYR) | NA | Y/$F_O$ | It means the ability of the process to exploit local resources. |
| Environmental Loading Ratio (ELR) | NA | N/R | It measures the influence on the environment from crop production |
| Emergy Sustainability Index (ESI) | NA | EYR/ELR | This index is to evaluate the sustainability of crop system |

Note: UEV and ELR are derived from Odum (1996) [35]; EYR and ESI are from Brown and Ulgiati (1997) [57]; $E_Y$: the energy yield of production system; Y: the emergy inputs of crop production system; $F_O$: purchased inputs from outside the system; N: total nonrenewable emergy; R: total renewable emergy.

## 3. Results

### *3.1. Emergy Input Structure*

In terms of the energy outputs, the average maize yield of monoculture during 2012 to 2014 is 9103 kg ha$^{-1}$. In a maize–soybean system, the average yields of maize and soybean are 6822 kg and 527 kg ha$^{-1}$ during 2012 to 2014, respectively. As shown in Table 4, the total emergy inputs to the monoculture and intercropping systems are 9.24E+15 sej and 1.56E+16 sej, respectively. Among the total energy inputs, natural environment resources inputs to the monoculture system (M) and intercropping system (MS) accounts for about 25% and 15%. The percentage rates for feedback from the economy or purchased resources in total emergy inputs is 75% in M and 85% in MS. This indicates that both cropping systems depend on externally purchased resources to a great extent in terms of total emergy inputs. The monocropping system (M) utilizes less purchased resources than the intercropping system (MS). The renewable resource input to M is 1.38E+15 sej and to MS is 2.17E+15 sej. Nonrenewable resources inputs are 7.86E+15 sej in M and 1.34E+16 sej in MS. Nonrenewable resources inputs of the two systems accounts for 85% in M and 86% in MS. It follows that both cropping systems make more use of nonrenewable resources; improving renewable resources utilization rate will reduce the impact on natural ecosystems.

The greatest emergy input for monocropped system (M) is electricity (29% of total emergy input) followed by nitrogen fertilization (17%) and labor (12%). For intercropping systems (MS), the greatest sources of emergy input are labor (48%), electricity (17%), and nitrogen fertilization (10%). From the proportion of total nonrenewable emergy input, in M treatments, emergy shares of electricity, as 31%, rank first, followed by nitrogen fertilization (19%), and labor (13%). Labor emergy, at 49%, ranks first in MS treatments, followed by electricity (18%), and nitrogen fertilization (11%). Electricity is mainly used to power irrigation. In general, both cropping systems should improve irrigation methods to reduce groundwater and electricity consumption. In order to reduce nitrogen fertilizer inputs, scientific fertilizer application by energy saving and reducing waste should be applied. For the MS treatments, labor makes up a large component of the emergy use, suggesting that reducing labor inputs is an important part of improving sustainable maize–soybean intercropping.

**Table 4.** Emergy analysis table of the cropping system (g/J ha$^{-1}$).

| Items | Unit | Class | RNF | UEV | M | | | MS | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | **Raw Data** | **Emergy** | **Renewable Emergy** | **Raw Data** | **Emergy** | **Renewable Emergy** |
| Natural environment resources (E) | | | | | | | | | | |
| Sun | J | L | 1.00 | 1.00E+00 | 1.18E+13 | 1.18E+13 | 1.18E+13 | 1.18E+13 | 1.18E+13 | 1.18E+13 |
| Wind | J | L | 1.00 | 2.45E+03 | 5.63E+08 | 1.38E+12 | 1.38E+12 | 5.63E+08 | 1.38E+12 | 1.38E+12 |
| Rain chemical energy | J | L | 1.00 | 3.10E+04 | 2.78E+10 | 8.61E+14 | 8.61E+14 | 2.78E+10 | 8.61E+14 | 8.61E+14 |
| Groundwater | J | L | 0.10 | 2.45E+05 | 3.71E+09 | 9.08E+14 | 9.08E+13 | 3.71E+09 | 9.08E+14 | 9.08E+13 |
| Soil net loss | J | L | 0.00 | 1.24E+05 | 4.23E+09 | 5.24E+14 | 0.00E+00 | 4.19E+09 | 5.19E+14 | 0.00E+00 |
| Feedback from the economy or purchased resources (F) | | | | | | | | | | |
| Fuel | J | $F_O$ | 0.00 | 1.11E+05 | 2.08E+09 | 2.31E+14 | 0.00E+00 | 2.08E+09 | 2.31E+14 | 0.00E+00 |
| Machine | g | $F_O$ | 0.00 | 1.13E+10 | 5.81E+04 | 6.57E+14 | 0.00E+00 | 5.81E+04 | 6.57E+14 | 0.00E+00 |
| Labor | J | $F_O$ | 0.12 | 7.56E+06 | 1.50E+08 | 1.13E+15 | 1.36E+14 | 9.79E+08 | 7.40E+15 | 8.88E+14 |
| Herbicide Pesticide | g | $F_O$ | 0.00 | 2.49E+10 | 7.50E+01 | 1.87E+12 | 0.00E+00 | 3.93E+01 | 9.79E+11 | 0.00E+00 |
| Electricity | J | $F_O$ | 0.09 | 2.87E+05 | 9.38E+09 | 2.69E+15 | 2.42E+14 | 9.38E+09 | 2.69E+15 | 2.42E+14 |
| N | g | $F_O$ | 0.00 | 6.38E+09 | 2.40E+05 | 1.53E+15 | 0.00E+00 | 2.40E+05 | 1.53E+15 | 0.00E+00 |
| $P_2O_5$ | g | $F_O$ | 0.00 | 6.55E+09 | 7.50E+04 | 4.91E+14 | 0.00E+00 | 7.50E+04 | 4.91E+14 | 0.00E+00 |
| $K_2O$ | g | $F_O$ | 0.00 | 1.85E+09 | 9.00E+04 | 1.67E+14 | 0.00E+00 | 9.00E+04 | 1.67E+14 | 0.00E+00 |
| Seed | g | $F_O$ | 1.00 | 1.11E+05 | 4.45E+08 | 4.93E+13 | 4.93E+13 | 8.40E+08 | 9.32E+13 | 9.32E+13 |
| Total emergy Input | | | | | | 9.24E+15 | 1.38E+15 | | 1.56E+16 | 2.17E+15 |
| Total energy Output | J | | | | 1.48E+11 | | | 1.22E+11 | | |

Note: M represents maize monocropping system; MS represents maize–soybean intercropping system; Fo represents purchased resources from outside system; L represents the local resources.

### 3.2. Emergy-Based Indices

#### 3.2.1. Unit Emergy Value (UEV)

The unit emergy value (UEV) is the ratio of total emergy inputs to total energy outputs [35], namely, how much emergy is needed for each unit of energy. From the formula, the higher the UEV is, for products with the same energy, the more emergy is needed. With the same emergy inputs, higher energy outputs are the concentrated reflection of systematic emergy use efficiency. From Table 5, the UEV of maize monoculture treatments calculated in this case is 6.23E+04 sej/j. UEV of maize–soybean intercropping treatments is 2.04 times that of maize monocropping treatments. Thus, maize monocropping has higher systematic emergy use efficiency than maize–soybean intercropping. This is due to both increased energy output and decreased emergy input of the monocropping system.

**Table 5.** Emergy indicators of the cropping system.

| Emergy Indices | M | MS |
| --- | --- | --- |
| Unit Emergy Value (sej/j) | 6.23E+04 | 1.27E+05 |
| Unit Nonrenewable Emergy Value (sej/j) | 5.30E+04 | 1.09E+05 |
| Emergy Yield Ratio (EYR) | 1.33 | 1.17 |
| Environmental Loading Ratio (ELR) | 5.70 | 6.15 |
| Emergy Sustainability Index (ESI) | 0.23 | 0.19 |

Note: M represents maize monocropping system; MS represents maize-soybean intercropping system.

#### 3.2.2. Unit Nonrenewable Emergy Value (UNV)

Unit nonrenewable emergy value is somewhat akin to the UEV. It is the ratio of nonrenewable resource emergy inputs divided by total energy outputs, namely, a system with stable stability needs less use of nonrenewable resources to reduce threat to the natural environment. Higher UNV in a cropping system reflects that high utilization rate of nonrenewable resources. In this study, the unit nonrenewable emergy value in the maize monoculture system and the maize–soybean intercropping system, respectively, are 5.30E+04 sej/j and 1.09E+05 sej/j. Compared to maize monocropping, intercropping relies more on nonrenewable resources.

#### 3.2.3. Emergy Yield Ratio (EYR)

Emergy yield ratio (EYR) is the ratio of total emergy inputs to the external purchased emergy input [35], and measures local resource availability through the inputs from external systems [47]. In other words, it is an evaluation of local resource utilization efficiency and the contribution to the economy and society around the system. As shown in Table 5, the EYR of maize monocropping treatments in this case is 1.33 and that of maize–soybean intercropping treatments is 1.17. From this we see that maize monocropping systems, compared to intercropping systems, can better exploit local resources, such as soil nutrients and organic matter, make more contributions to external economic systems and have competitive power in the market.

#### 3.2.4. Environmental Loading Ratio (ELR)

Environmental loading ratio (ELR) is a ratio of inputs of nonrenewable resource emergy to renewable resource emergy inputs, which is an indicator about the pressures of processes on local ecosystems or the ecosystem stress caused by production activity. The ELR obtained in this experiment of maize monocropping is 5.70. For the maize–soybean intercropping system, the ELR is 6.15 (Table 5). These results suggest that maize–soybean stress the local environment. From the ratio of ELR, higher non-renewable resource emergy input would cause higher pressure on local environment. The reasons leading to higher ELR of maize–soybean intercropping systems are that total labor input takes 49% of total non-renewable emergy input and the weeding and harvesting processes take major labor input.

The root cause is that the maize–soybean intercropping system has distinct biological characteristics, which affect mechanization management.

#### 3.2.5. Emergy Sustainability Index (ESI)

The emergy sustainability index (ESI) is calculated by a ratio of EYR to ELR, and reflects the sustainability of a system. Brown and Ulgiati (2004) [58] proved that ESI values between 1 and 10 have been termed "developing economies". We find the ESI of maize monocropping in this experiment is 0.23, while the ESI of maize–soybean intercropping is 0.19 (Table 5), indicating that maize monocropping has greater sustainability than maize–soybean intercropping. Controlling the growth rate of environmental loading (ELR) could provide a means in the future to achieve a sustainable system.

### *3.3. Multiple Nitrogen Fertilizer Application Levels on Intercropping*

In terms of the energy output, the data in Table 6 indicates that the UVE and UNE appear optimal under the MS120 treatment. As to EYR and ESI, two indices between MS120 and MS180 treatments are nearly identical; however, the ELR of MS120 treatments is less than that of MS180 treatments. All emergy indices of MS treatment appear worst among three treatments. It follows that more externally purchased resources emergy input and more nonrenewable resources emergy inputs are used in the MS treatment. Namely, MS120 treatments present more ecological sustainability among three N fertilizer application treatments. In conclusion, with the reduction of N fertilizer application rate, the system presents less nonrenewable resource input, lower external purchased emergy inputs, higher natural resources utilization rate and has better sustainability. However, the maize–soybean intercropping with lower nitrogen fertilizer application still has less overall sustainability than maize monocropping.

**Table 6.** Emergy indicators of the different N application for intercropping system.

| Emergy Indices | MS120 | MS180 | MS |
|---|---|---|---|
| Unit Emergy Value (sej/j) | 1.25E+05 | 1.27E+05 | 1.27E+06 |
| Unit nonrenewable Emergy value (sej/j) | 1.06E+05 | 1.08E+05 | 1.09E+05 |
| Emergy yield ratio (EYR) | 1.18 | 1.18 | 1.17 |
| Environmental loading ratio (ELR) | 5.79 | 5.97 | 6.15 |
| Emergy sustainability index (ESI) | 0.20 | 0.20 | 0.19 |

Note: MS represents maize–soybean intercropping system.

## 4. Discussion

### *4.1. Sustainability on Cropping Systems from Emergy Evaluation*

In recent years, emergy evaluation has been widely applied in agroecological analysis, which weighs the intercropping evaluation not only in terms of material input–output, but also from material energy aspects. The common metric, solar emergy, analyzes the resources that methods ignored before. Application of the emergy methodology to intercropping systems is a new approach which can mediate the conflicting goals of protecting the environment and reducing resources input within a systematic production. However, because of the strengths researchers found in cereal–legume intercropping, on the premise of ensuring the maize production, it has been proposed that developing maize–soybean intercropping will improve the ecological function of the maize production area, which would be beneficial in the North China Plain [13]. Therefore, this paper focuses on the comparison between maize monocropping and maize–soybean intercropping; however, in order to perform a rigorous evaluation of intercropping, we should further discuss both sole crops involved in the intercropped system in future research [59]. In this study, although recent research has suggested that intercropping is optimal for enhancing resource utilization efficiency and attaining higher yield, maize–soybean intercropping does not show significantly better performance than maize monocropping, which results from less energy output and much greater requirements for input in maize–soybean intercropping, particularly for labor from an energy point of view. In terms of emergy-based indices accounting for local emergy inputs and purchased inputs from outside the system [57], the labor inputs are paid by salary within this system boundaries, which was deemed as outside input from an emergy perspective. Because of spatial heterogeneity of maize and soybean, herbicide cannot be applied in maize–soybean treatments with interaction between crops and it costs more in labor input to do weeding, which occupies 72% in total labor input. Moreover, soybean has no suitable technology for machine harvesting at present and needs an artificial harvesting method, which takes 16% of total labor input. According the RNF and solar transformity of labor emergy, labor emergy input takes up a large proportion in intercropping systems compared to the monocropped maize system, which correspondingly increases the nonrenewable emergy input. What is worth mentioning is that technology development could achieve mechanical harvesting on intercropping systems [60]; agricultural technology needs to be developed to enhance the resource allocation and utilization efficiency for intercropping systems

### 4.2. Reduction on Fertilizer for Intercropping

Nitrogen fertilizer is a key emergy input that influences the sustainability of intercropping systems like the one studied here. The maize–soybean intercropping systems require less N fertilizer because the legume crop can rely on biological $N_2$ fixation and the soil N uptake to meet its requirements for maximum yield [26]. Hence, it is important to investigate the sustainability on reduction of application rate of nitrogen fertilizer. Moreover, different N application rates result in yield change. According to experimental data from 2012 to 2014, under the N application rate of 120 kg ha$^{-1}$, the three-year average yield of maize and soybean, respectively, is up to 6714 kg ha$^{-1}$ and 429 kg ha$^{-1}$. The three-year average yield comes to 6671 kg ha$^{-1}$ in maize and 526 kg ha$^{-1}$ in soybean when the N fertilizer applied is 180 kg ha$^{-1}$. Besides, the average yields of maize and soybean under 240 kg ha$^{-1}$ N fertilizer rate are 6822 and 527 kg ha$^{-1}$ during 2012 to 2014, respectively. Considering system inputs and outputs, we find that soybean yield has no significant differences between application rates of 180 kg ha$^{-1}$ and 240 kg ha$^{-1}$. On the contrary, when the N fertilizer is applied for 240 kg ha$^{-1}$, the yield of maize reaches the maximum. The maize–soybean intercropping with lower nitrogen fertilizer application still has less overall sustainability than maize monocropping. We have shown that the primary reasons are decreased energy output and a larger proportion of labor input in the intercropping system. There is thus an urgent need for suitable machine research and technical development to decrease labor inputs in intercropping systems, which should take place alongside ongoing research into other management practices to improve the sustainability and potential of intercropping systems, such as improved irrigation water use efficiency methods [61] and different tillage systems [62].

## 5. Conclusions

This study compares the maize monocropping pattern with the maize–soybean intercropping pattern based on emergy analysis. The results show that, compared to the maize–soybean intercropping system, the maize monocropping system has better environmental performances and sustainability in the North China Plain. Reduction of the nitrogen fertilizer application rate in intercropping systems could decrease the nonrenewable resources input and improve sustainability. However, the maize–soybean intercropping system with less nitrogen fertilizer application still has lower sustainability than maize monocropping, which is mostly due to a large level of labor input and lower energy output. Currently, agronomic operations and agricultural technology need to be developed to enhance the resource allocation and utilization efficiency for intercropping systems, which would lay a good foundation for agricultural sustainable developments and cropping diversity.

**Author Contributions:** X.Y. wrote the original draft. Y.S. and D.W. provided resources. X.W. analyzed the data. J.S.G., Y.C., P.S., and H.D. edited the paper.

**Funding:** This research was funded by the National Key Research and Development Program of China grant number 2016YFD0300210 and 2016YFD0300203.

**Acknowledgments:** We thank anonymous reviewers and editors for very helpful comments and suggestion of the manuscript.

**Conflicts of Interest:** The authors declare no conflict of interest.

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