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Valuing the synergy in the water-energy-food nexus for cropping systems: a case in the North China Plain

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ABSTRACT

Extreme climate change, rapid population growth and economic development drive a growing demand for resources, which lead to energy, food, water and their intertwined nexus becoming increasingly important. Agricultural decisions considering the interconnections among water, energy, and food are critical. The consumption of large amounts groundwater and non-renewable energy by the predominant traditional wheat-maize cropping system has caused a serious water shortage in the North China Plain (NCP), which is a large food production region in China. This situation has strained the relationship between water/energy consumption and food production. It is important to seek synergy in the water-energy-food nexus. This paper proposed a relative index of water-energy-food (WEF_{RI}) based on different values of resource consumption and use efficiency between treatment systems and control system to analyze the synergy between water utilization, energy consumption and food supply in different cropping systems at the field scale. The goal is to seek a sustainable cropping system to balance crop production while reducing energy consumption and water depletion. In this case, different systems including monocropped maize (*Zea mays*) (MM), intercropped maize and soybean (*Glycine* max) (MS), relay cropped of maize with pea (*Pisum sativum*) (MP) and potato (*Solanum tuberosum*) (MO), rotation of maize with spinach (*Spinacia oleracea*) (MI) and ryegrass (*Secale cereale*) (MR), and using traditional wheat-maize (*Triticum aestivum*) (MW) as a control. MM, MS, MP and MO were the best systems within a particular range of food supply reduction. The WEF_{RI} of the MM/MS system was the highest (2.96/2.78). Compared to the MW system, the groundwater consumption of MM/MS was reduced by 73.84%/73.84%, and non-renewable energy inputs were reduced by 48.01%/48.30%; however, the food supply decreased by 48.05%/51.70%. The WEF_{RI} of the MP system was 1.98. In comparison with the MW system, the groundwater consumption of the MP system was reduced by 28.46%, and the non-renewable energy inputs were reduced by 42.68%. However, the food supply decreased by 37.13%. The WEF_{RI} of MO system was 1.92. Compared to the MW system, the groundwater consumption of MO was reduced by 11.47%, non-renewable energy inputs were reduced by 32.14%, and the food supply only decreased by 26.27%. In conclusion, we theoretically proposed the following references for cropping systems in the NCP: MM and MS are implemented when the areas has extreme water shortages, MO is implemented when a less than 30% reduction in the food supply capacity is acceptable, and MP is recommended if a 30%–40% reduction in the food supply is acceptable.

1. Introduction

Water, energy and food are essential elements for human subsistence, and they are also critical global resources that are intrinsically linked to environmentally sustainable development. Population growth and economic development have a direct effect on the demand for water, energy and food (Chai et al., 2020). It is estimated that the world population will reach approximately 10 billion by 2050 (United Nations, 2017). Therefore, it will have to invest a large amount of limited water and energy to obtain sufficient food for all of these people (El-Gafy, 2017).

Energy consumption promotes rapid development of economic, but

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it also causes expanding consumption of water resources (Zhang et al., 2019). Energy and water demand in China has been forecasted to increase by up to 8% and 5%, respectively, from 2020 to 2030 (Chai et al., 2020). Furthermore, there is an inseparable nexus between water, energy and food directly and indirectly: water is required to irrigate crops in the field and further produce food; energy is used for machine operation, fertilizer production, water collection and transportation to access food; water is needed for cooling during energy generation processing; irrigation water is pumped, extracted, lifted, and distributed to growing crops by applying the power of the energy in the field. In addition, a proportion of the clean energy comes from hydropower and biofuels. The close relationship between water, energy and food makes it impossible to consider one aspect alone. Therefore, it is necessary to understand the complex nexus between water, energy and food (El-Gafy, 2017). Using this relationship suitably is of great significance for the sustainable development of resources and human society.

The concept of the water-energy-food (WEF) nexus was first formally put forward in the Bonn 2011 Nexus Conference (Hoff, 2011). The German Federal Government, the United Nations University (UNU), the Food and Agriculture Organization (FAO) and some global authoritative institutions clarified the notion of the WEF nexus from different perspectives (Endo et al., 2017). There have been many qualitative and quantitative studies on the WEF nexus over the years. Through qualitative analysis, the researchers provided a theoretical foundation for quantitative analysis of the WEF nexus. For example, Kimmich et al. (2019) accomplished a participatory model that could result in new adaptive capacities, collective actions, and shared views. Purwanto et al. (2019) established a WEF nexus qualitative causal model by using the group model to enhance the understanding of different sectors and improve quantitative analysis. In addition, some scholars generalized some key frameworks and models for the WEF nexus in the published literatures (Dargin et al., 2019; Schull et al., 2020), articulating how to move from nexus thinking to quantitative analysis of actionable concepts (McGrane et al., 2019).

In terms of quantitative research, there are some important tools that illustrate the connections of water, energy, and food, as well as economic and environmental factors, such as the input–output model (Deng et al., 2020), life cycle assessment (LCA) (Ghani et al., 2019), system dynamics (SD) (Ravar et al., 2020; Bakhshianlamouki et al., 2020) and Bayesian networks (Chai et al., 2020). However, these studies analyzed the three departments of energy production, water resources and food and their linkages in a holistic way within cities, river basins or national regions. To more comprehensively understand and apply the WEF nexus, different scales of WEF nexus research are required (IUCN, 2019; McGrane et al., 2019).

Agriculture is the chief driving force of water, energy, and food security, consuming approximately 70% of the total global fresh water resources exploitation amount and 30% of the total global energy by food production and its supply chain (Liu et al., 2019; FAO, 2012). From 1961 to 2014, energy (consumed by machinery, fuel, and fertilizer) consumption in planting industry accounted for approximately 3% of the world's primary energy, and meantime energy consumption per unit farmland area increased by 137% (FAO, 2011b; Pellegrini and Fernández, 2018). Consequently, it is urgent to study the water-energy-food nexus of the crop production system in farmland. El-Gafy (2017) developed an approach to analyze the WEF nexus in the process of food production, and the method was applied to multiple Egyptian food crops. Liu et al. (2019), based on the WEF nexus, constructed a matter–element model to assess agricultural sustainability for one irrigation zone in China. Pitak et al. (2019) and Li et al. (2019) provided the methods of the WEF nexus relationship to analyze crop production systems at the watershed scale in Thailand and China, respectively.

The North China Plain (NCP), one of the main food producing areas, is also the world's largest groundwater subsiding region, where the relationship between groundwater resources and agricultural production is strained (Tian et al., 2020; Chen et al., 2020). However, as far as we know, there are currently no existing studies of the water-energy-food nexus for field crops in the NCP. Wheat-maize is a major cropping system in the NCP, producing wheat and maize in more than 75% and 32% of the nation's total, respectively (Chang et al., 2020). However, 76.7% of groundwater extraction was used for agriculture in the NCP (Chen et al., 2020). The high inputs of water and fertilizer produced a high yield, but also led to the problems of a decreasing groundwater level, intensified greenhouse gas emissions from farmland, and increased energy consumption, further aggravating the contradiction between water resources and food production, which seriously threatens sustainable resource development (Xu et al., 2005; Zhang et al., 2020; Cui et al., 2018).

Therefore, our objectives were to valuate the synergy in the WEF nexus for seven cropping systems at the field scale in the NCP and to provide a theoretical basis for the selection of the most appropriate cropping systems in different resource backgrounds. For the purpose of this study, we made little change to the previous WEF index study (El-Gafy, 2017; Gathala et al., 2020) and proposed a relative index to find an alternative cropping system to wheat-maize. The study would promote the application of the WEF nexus studies in the evaluation of cropping systems in the NCP, balancing water use, energy consumption and crop production in the crop planting.

2. Materials and methods

2.1. Site description

The trial was installed in 2014, and the experimental data used in this article were collected from 2015 to 2019. The experiments were conducted at Wuqiao Experimental Station of China Agricultural University located in Hebei Province, the NCP (37°41′02″N, 116°37′23″E). The area has a temperate monsoon climate with a frost-free period of 201 days and a daily mean temperature of 12.9 ℃. The mean annual precipitation was 581 mm (1970–2019), peaking from June to September. The soil is classified as sandy loamy soil, and the properties of the initial soil are as follows: organic C, 11.38 g kg^{-1}; total N, 0.54 g kg^{-1}; available P, 41.55 mg kg^{-1}; and available K, 45.73 mg kg^{-1}.

2.2. Experimental design

The NCP is one of the main grain-production areas in China, but the traditional wheat-maize cropping system consumes a lot of water and energy resources. We added vegetables, tubers, beans and forages according to the needs of the local farmers in this experiment. The wheat and maize double cropping (MW) was set as a control, and the treatments included intercropping maize and soybean (MS), relay cropping maize with pea (MP) and potato (MO), rotation of maize with spinach (MI) and ryegrass (MR), and monocropped maize (MM). The trial design was completely randomized with 3 replicates and plots with dimensions of 7 × 9 m (63 m^2).

In this experiment, the number of maize plants in a hectare was 55,550 in all treatments. Maize in the MW, MM, MI, and MR systems of plant spacing was 30 cm apart, and the row spacing was 60 cm (Fig. 1a). Intercropping and relay cropping systems were wide-narrow rows planted with a wide row of 80 cm and a narrow row of 40 cm. There was one row of soybean/potato (Fig. 1b) and two rows of peas (Fig. 1c) in the wide row. Spinach was dispersed on the land. Ryegrass and wheat were sown in lines with a row spacing of 15 cm (Fig. 1d).

2.3. Purpose and indexes

The purpose of the study is to develop an index evaluation method for the water, energy and food nexus of cropping systems at the field scale. This method can be used to coordinate the three aspects of water, energy and food to obtain an integrated evaluation index and to analyze the relationship between the water/energy consumption and the food

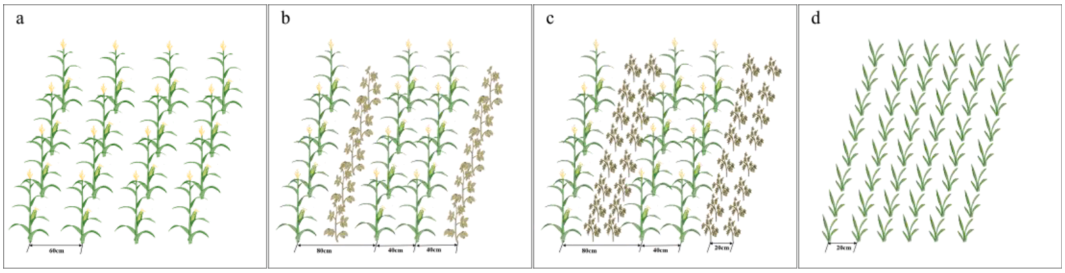

Fig. 1. Schematic diagram of crops planted in the field.

output of the different cropping systems. Therefore, some critical indicators related to the water, energy and food production of cropping systems in farmland were selected in this study, such as total water consumption (irrigation water, precipitation), total energy consumption (non-renewable energy, renewable energy), and food supply capacity (crop energy output).

2.3.1. Energy indicators

The total amount of energy consumption (E_i; MJ ha^{-1}) in this study is artificially referred to the energy input. It includes direct (ED_i; MJ ha^{-1}) and indirect (EI_i; MJ ha^{-1}) input. Direct energy consumption is the diesel and electricity required to operate machinery, and indirect energy consumption is the energy expended in pesticide and fertilizer production for crop production (El-Gafy, 2017). Additionally, the energy inputs include non-renewable energy (EN_i, MJ ha^{-1}) and renewable energy (ER_i, MJ ha^{-1}). The ED_i, EI_i, EN_i, and ER_i of the i cropping system (all treatments and control system) calculation formulas were:

$$E_i = ED_i + EI_i \tag{1}$$

$$ED_i = ED_i^l + ED_i^e + ED_i^u \tag{2}$$

$$EI_i = EI_i^f + EI_i^p + EI_i^s + EI_i^a \tag{3}$$

$$EN_i = ED_i^e + ED_i^u + EI_i^f + EI_i^p + EI_i^a \tag{4}$$

$$ER_i = EI_i^s + ED_i^l \tag{5}$$

where ED_i^l is the manual energy from human labor (MJ ha^{-1}); ED_i^e is the energy consumed by electricity for irrigation; ED_i^u is the energy of diesel fuels for ploughing, planting and harvesting (MJ ha^{-1}); and EI_i^f, EI_i^p, $EI_i^s$and EI_i^a are the energy consumption from fertilizer, pesticides, seeds and machinery (MJ ha^{-1}). The energy terms were the inputs used in each category multiplied by the relevant energy-equivalent factor, which are shown in Table 1.

2.3.2. Water indicators

The total water consumption (W_i; m^3 ha^{-1}) was the amount of precipitation (WP_i; m^3 ha^{-1}) during the crop growth period and the irrigation groundwater (WG_i; m^3 ha^{-1}) consumed to produce crops in the field. The effective precipitation excluded the amount of water lost to runoff and that intercepted by plants. We used a simple approximation by following the U.S. Department of Agriculture Soil Conservation Method and its calculation formulas were (Fan et al., 2020; Martin, 1992):

$$WE_i = \begin{cases} WP_i \times (4.17 - 0.2 \times WP_i)/4.17, WP_i < 8.3 \text{ mmd}^{-1} \\ 4.17 + 0.1 \times WP_i, WP_i \geq 8.3 \text{ mmd}^{-1} \end{cases} \tag{6}$$

$$WN_i = WP_i - WE_i \tag{7}$$

Where WE_i is the daily effective precipitation in the i cropping system (mm d^{-1}); WP_i is the daily precipitation in the i cropping system (mm d^{-1}); and WN_i is the daily non-available precipitation in the i cropping system (mm d^{-1}).

Table 1
Energy equivalent for the inputs relevant to cropping systems.

Item	Unit	Energy equivalent (MJ unit^{-1})	Reference
1. Machinery	h	13.06	(Pishgar-Komleh et al., 2013)
2. Chemical fertilizer			
(a) Nitrogenous (N)	kg	66.14	(Erdal et al., 2007)
(b) Phosphate (P_2O_5)	kg	12.44	(Erdal et al., 2007)
(c) Potash (K_2O)	kg	11.15	(Erdal et al., 2007)
3. Diesel fuel	L	51.33	(Samavatean et al., 2011)
4. Electricity for irrigation	kWh	3.6	(Rafiee et al., 2010)
5. Pesticides			
(a) Herbicides	kg	238	(Singh et al., 2019)
(b) Insecticides	kg	199	(Singh et al., 2019)
(c) Fungicides	kg	216	(Singh et al., 2019)
6. Labor	h	1.96	(Pishgar-Komleh et al., 2013)
7. Seeds			
(a) Maize	kg	14.7	(Chamsing et al., 2006)
(b) Wheat	kg	17.6	(Singh et al., 2019)
(c) Soybean	kg	25	(Chamsing et al., 2006)
(d) Pea	kg	14.2	(Nguyen and Haynes, 1995)
(e) Potato	kg	5.1	(Singh et al., 2016)
(f) Spinach	kg	0.8	(Singh et al., 2016)
(g) Ryegrass	kg	18.4	(Nguyen and Haynes, 1995)

2.3.3. Food indicators

We used the indicator of food supply to represent one part of food security. Food supply referred to the amount of energy that humans can directly obtain from the edible parts of harvested crops. Different crops have different nutrients per unit mass and therefore different energies (Sadeghi et al., 2020). The crops calculated here were all plants cultivated in this research. The food supply calculation formula was:

$$F_i = \sum 239 C_i^k \alpha_k \tag{8}$$

where F_i is the total food supply of crop k in cropping system i (MJ ha^{-1}); C_i^k is the edible yield of crop k in cropping system i (kg ha^{-1}); and α_k is the energy coefficient of crop k (kcal kg^{-1}) (Yang, 2018; Shi et al., 2015). It is worth noting that ryegrass, as a forage grass, was converted into energy directly used by humans according to the energy conversion efficiency of the ecosystem of 1:9.29 (Lou et al., 2019).

2.3.4. Relative index of the water-energy-food nexus (WEF_{RI})

This study presents the water-energy-food nexus relative index (WEF_{RI}) of cropping systems at the field scale. The higher of the WEF_{RI} value is the more balanced tradeoff among water, energy and food resources for the cropping system. The $WEF_{RI\,j}$ of the j cropping system was calculated by the following formulas:

$$WEF_{RI,j} = I_{w,j} + I_{e,j} \tag{9}$$

$$I_{w,j} = (\Delta F_j + 1)/(\Delta WG_j + 1) \tag{10}$$

$$I_{e,j} = (\Delta F_j + 1)/(\Delta EN_j + 1) \tag{11}$$

where the j refers to cropping system excluding the control cropping system, and the control system ct is the wheat-maize double cropping in the study. $I_{w,j}$ is the sub-index of water in cropping system j; $I_{e,j}$ is the sub-index of energy in cropping system j; ΔWG_j is the increased percentage of cropping system j over the control cropping system in irrigation water consumption; ΔEN_j is the increased percentage of cropping system j compared to the control in non-renewable energy consumption; ΔF_j is the increased percentage of cropping system j compared to the control cropping system in food supply capacity. The ΔWG_j, ΔEN_j, and ΔF_j of the j cropping system were calculated as follows:

$$\Delta WG_j = (WG_j - WG_{ct})/WG_{ct} \tag{12}$$

$$\Delta EN_j = (EN_j - EN_{ct})/EN_{ct} \tag{13}$$

$$\Delta F_j = (F_j - F_{ct})/F_{ct} \tag{14}$$

where WG_{ct}, EN_{ct}, and F_{ct} are the irrigation water (m^3 ha^{-1}), non-renewable energy (MJ ha^{-1}), and total food supply (MJ ha^{-1}) in the control cropping system, respectively; WG_j, EN_j, and F_j are the irrigation water, non-renewable energy, and total food supply in cropping system j, respectively.

2.4. Data collection and analysis

The precipitation data were collected from the Wuqiao County Meteorological Bureau. The date of agricultural inputs (e.g., human labor, machinery, diesel oil, fertilizer, pesticides, seeds, and irrigated water) and outputs were obtained from the observations of the field experiments (Table 2).

3. Results

3.1. Energy indicators

As shown in Fig. 2, the total energy inputs of the different cropping systems were 33364–69138 MJ ha^{-1}. The total energy inputs of the MW control system were the highest, and the total energy inputs of the MM and MS systems were the lowest, which nearly decreased by 52% compared with the MW system. In comparison with the MW system, the total energy inputs of the MR, MI, MO and MP systems decreased by 30.75%, 24.26%, 23.33% and 45.42%, respectively. The energy consumption of MI was higher than that of MR, mainly due to the application of nitrogen fertilizer. Among all inputs of the different cropping systems, chemical fertilizer had the largest share (48%–65%), with N (37%–59%) in the first place, followed by K_2O (2%–8.41%) and P_2O_5 (1.76%–3.74%). Then, diesel energy contributed 13.84%–25.94%, which was mainly utilized for the operation of machinery with ploughing, sowing and harvesting. Diesel was followed by electricity (8.01%–18.13%), which was used for pumping and transporting groundwater to irrigate. The energy inputs of seeds, human labor, pesticides, and machinery contributed 0.87%–17.83%, 0.61%–1.50%, 0.25%–1.52% and 0.06%–0.11%, respectively. The wheat-maize double cropping system consumed most of the energy. Nitrogen fertilizer, diesel fuel for the operating machinery, and electricity for irrigation accounted for a large proportion of the total energy consumption, therefore, reducing nitrogen fertilizer and irrigation water inputs and improving machinery efficiency may be ways to reduce the energy inputs of farmland.

Table 3 demonstrates the different energy forms of direct energy, indirect energy, renewable energy, and non-renewable energy, and their percentages for the different cropping systems. The total energy inputs were classified as direct energy (32.42%–43.32%) and indirect energy (56.68%–67.58%). All cropping systems rely on external indirect energy to a great extent in terms of their total energy inputs. In all cropping systems, we could see reductions in indirect energy inputs from an MW system baseline of 23.92% in MO, 27.98% in MI, 41.87% in MR, 50.32% in MP, 51.18% in MS and 51.87% in MM. The renewable energy inputs of all cropping systems were 601–10244 MJ ha^{-1}, and the non-renewable energy inputs were 32585–63022 MJ ha^{-1}. The non-renewable energy inputs of the different systems reached 80.67%–98.38% in all inputs. Non-renewable energy inputs were lower than those of the MW control system in all treatment systems: by 18.26% in MI, by 28.44% in MR, by 32.14% in MO, by 42.68% in MP, by 48.01% in MM and by 48.3% in MS, indicating that all cropping systems make greater use of non-renewable resources.

3.2. Water indicators

The water inputs of the different cropping systems are shown in Table 4, including non-available precipitation, effective precipitation and irrigation water. The rainfall during the growth period of the different cropping systems was 3726–6989 m^3 from 2015 to 2019. Comparing the rainfall of the different cropping systems in the five-year growing period (Table 4), it could be seen that the rainfall during the growth periods in 2015, 2017, and 2019 was lower than that in 2016 and 2018, among which, the rainfall during the growth period of 2018 (the highest precipitation) increased by 35.56%–96.6% compared with

Table 2
Average inputs of the cropping systems in 2015–2019.

Item	unit	MW	MM	MR	MI	MO	MP	MS
1. Machinery	h ha^{-1}	4.00	2.70	4.17	3.56	2.46	2.46	2.70
2.Chemical fertilizer								
(a) Nitrogenous (N)	kg ha^{-1}	525.00	300.00	327.00	450.00	300.00	300.00	300.00
(b) Phosphate (P_2O_5)	kg ha^{-1}	187.50	75.00	144.00	120.00	75.00	75.00	75.00
(c) Potash (K_2O)	kg ha^{-1}	315.00	90.00	90.00	150.00	400.00	90.00	90.00
3. Irrigation	m^3 ha^{-1}	2790.00	730.00	2178.00	2113.00	2470.00	1996.00	730.00
4. Diesel fuel	L ha^{-1}	241.88	155.63	241.88	206.63	142.88	142.88	155.63
5. Electricity	kWh ha^{-1}	2665.00	750.00	2225.00	2150.00	2600.00	1900.00	750.00
6. Pesticides								
(a) Herbicides	kg ha^{-1}	1.00	0.50	0.50	0.50	0.00	0.00	0.00
(b) Insecticides	kg ha^{-1}	0.12	0.06	0.06	0.06	3.06	0.36	0.09
(c) Fungicides	kg ha^{-1}	0.60	0.60	0.30	0.30	0.90	0.30	0.30
7. Labor	h ha^{-1}	224.00	104.25	161.11	201.00	405.50	185.50	125.25
8. Seeds								
(a) Maize	kg ha^{-1}	27.00	27.00	27.00	27.00	27.00	27.00	27.00
(b) Others	kg ha^{-1}	300.00	0.00	112.50	75.00	1775.00	60.00	20.00

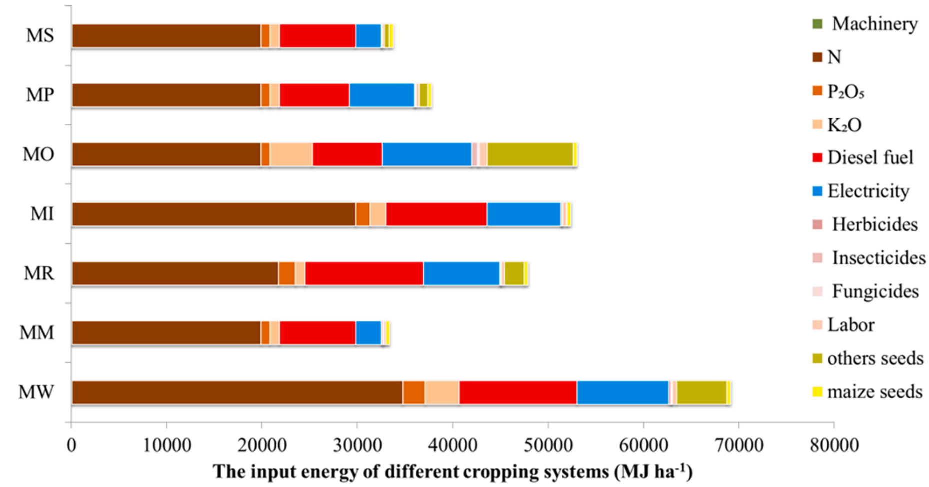

Fig. 2. Energy inputs of the different cropping systems. Note: MW represents wheat-maize double cropping system; MM represents maize monocropping system; MR represents maize-ryegrass double cropping system; MI represents maize-spinach double cropping system; MO represents maize-potato relay intercropping system; MP represents maize-pea relay intercropping system; MS represents maize-soybean intercropping system.

Table 3
Total energy inputs in the different forms in cropping systems.

Item	ED_i		EI_i		ER_i		EN_i	
	En	%	En	%	En	%	En	%
MW	22,449	32.47	46,689	67.53	6116	8.85	63,022	91.15
MM	10,893	32.65	22,471	67.35	601	1.80	32,763	98.20
MR	20,741	43.32	27,140	56.68	2783	5.81	45,099	94.19
MI	18,740	35.79	33,627	64.21	851	1.62	51,517	98.38
MO	17,489	32.99	35,520	67.01	10,244	19.33	42,764	80.67
MP	14,538	38.53	23,196	61.47	1612	4.27	36,121	95.73
MS	10,934	32.42	22,793	67.58	1142	3.39	32,585	96.61

Note: ED_i, EI_i, ER_i and EN_i represent direct energy, indirect energy, renewable energy and non-renewable energy respectively; En represents the amounts of total energy inputs, MJ ha^{-1}.

Table 4
Water inputs of different cropping systems in 2015–2019 (m^3 ha^{-1}).

Year	Input Water	MW	MM	MR	MI	MO	MP	MS
2015	Effective precipitation	/	2522	3895	/	3587	3587	2522
	Non-available precipitation	/	1204	1412	/	1777	1603	1204
	Irrigation water	/	750	2200	/	2450	1850	750
2016	Effective precipitation	4118	3732	4514	4414	3448	3892	3732
	Non-available precipitation	1923	2065	2139	2134	3419	2204	2065
	Irrigation water	3000	650	1950	1300	2300	2350	650
2017	Effective precipitation	3586	2726	3678	3325	2488	3171	2726
	Non-available precipitation	867	821	872	846	1341	997	821
	Irrigation water	2750	750	2200	2050	3200	2300	750
2018	Effective precipitation	3654	2470	3060	3031	3082	3717	2470
	Non-available precipitation	3335	2788	3108	3107	4446	3737	2788
	Irrigation water	2580	750	2250	2250	2000	1500	750
2019	Effective precipitation	3061	2566	3061	2818	2949	2949	2566
	Non-available precipitation	2053	2009	2053	2021	2305	2305	2009
	Irrigation water	2830	750	2290	2850	2400	1980	750
Annual average	Effective precipitation	3605	2803	3642	3222	3111	3463	2803
	Non-available precipitation	2045	1777	1917	1863	2658	2169	1777
	Irrigation water	2790	730	2178	2113	2470	1996	730
	All water input	8439	5311	7736	7197	8238	7628	5311

that in 2017 (the least precipitation). However, the irrigation water of MW, MO, and MP relative to 2017 decreased only by 6.18%–37.5% in 2018. The irrigation water of the MM and MS systems in 2017 and 2018 was the same. The irrigation water of the MR and MI systems was higher in 2018 than in 2017. In terms of the effective rainfall for different cropping systems, MW, MO, and MP in 2018 were only higher than in 2017 by 1.91%–23.84%, and MM, MR, MI, and MS in 2018 were lower than in 2017 by 8.85%–9.39%. It could be seen from the above analysis that water for irrigation of the different cropping systems was affected by the effective rainfall during the growth period, and the coupling of the rainfall period with the growth period was very important for irrigation water.

The annual average water inputs are shown in the following order: MS = MM < MI < MP < MR < MO < MW (Table 4). The system with the largest amount of irrigation water was the control group MW, which was 2790 m^3. The MM and MS systems had the least irrigation water, which was 730 m^3. Compared to the MW control system, the MP, MI, MR and MO systems had decreased irrigation water by 28.46%, 24.28%, 21.94% and 11.47%, respectively. The total precipitation during the growth period of the different systems was 4580–5768 m^3, and the effective precipitation only accounted for 54%–66% of the total precipitation. One of the reasons for the low effective precipitation during the growth period may be the uneven distribution of rainfall in the NCP, with more than 70% of the rainfall occurring in June, July, August and September.

3.3. Food supply indicators

The food supply for each cropping system is shown in Table 5. The annual average food supply of the MW system was 295210 MJ ha^{-1}, which was the highest among all systems. The annual average food supply of the MO, MI, MP, MR, MM and MS systems decreased by 26.27%, 33.39%, 37.13%, 41.93%, 48.50% and 51.70%, respectively, compared to the MW system. The annual average food supply of the MO system was significantly higher than that of the MM, MR and MS systems, and there was no significant difference among the MO and MI systems. In terms of food supply in different years, the food supply of the MO and MR systems in 2015 and the MO system in 2016 were significantly higher than in the other years. The MW system all along had the greatest food supply in 2017–2019. The annual food supply of the treatment systems had decreased by 24%–50% in 2017, 34%–56% in 2018 and 14%–56% in 2019 as compared to the MW system.

3.4. Relative index of the water-energy-food nexus

In general, the effects of groundwater resource inputs, non-renewable energy consumption and food supply capacity of the cropping systems were often not the homodromous. Therefore, we combined water, energy and food together for comprehensive analysis (Table 6). The groundwater irrigation and non-renewable energy consumption of the MM and MS systems were the lowest (Table 3, Table 4). The groundwater irrigation consumption of the MM and MS systems was 73.84% lower than that of the MW control system; the non-renewable energy inputs of the MM and MS systems were 48.01% and 48.30% lower than those of the MW control system. Both I_e and I_w of the MM cropping system were higher than those of MS. The WEF_{RI} of the MM system (2.96) was higher than the MS (2.78), while the WEF_{RI} of MM and MS were the highest among all cropping systems. Therefore, the MM and MS systems are enormously beneficial to the sustainable development of water and energy resources. However, the food supply of the MM and MS systems was reduced by more than 40% relative to the MW control system, which may have adverse implications for food security. Similarly, the MR system also reduced the food supply by more than 40%, but the WEF_{RI} (1.55) of the MR system was lower than that of the MM (2.96) and MS (2.78) systems. Therefore, the MM and MS cropping systems are implemented in areas with extreme water shortages.

Table 5
Food supply in different cropping systems (MJ ha^{-1}).

Item	2015	2016	2017	2018	2019	Average
MW	/	/	307788 ± 5700a	280374 ± 9835a	297468 ± 16391a	295210 ± 13845a
MM	164877 ± 2562b	130796 ± 9205d	154265 ± 4382d	136198 ± 4767d	174032 ± 22830c	152034 ± 18410e
MR	203329 ± 5059a	153088 ± 4809c	168483 ± 15328d	159216 ± 5208c	172960 ± 5486c	171415 ± 19456 cd
MI	/	184436 ± 16342b	234996 ± 10644b	182380 ± 2588b	184797 ± 13157c	196653 ± 25585bc
MO	212703 ± 9790a	203408 ± 13823a	229590 ± 10599b	186444 ± 21097b	256218 ± 22862b	217673 ± 26604b
MP	178801 ± 8498b	150115 ± 1654c	198888 ± 9313c	156097 ± 3594c	244071 ± 9912b	185594 ± 37984bcd
MS	167876 ± 11098b	125222 ± 9784d	163592 ± 14261d	123977 ± 3434d	132200 ± 24985c	142573 ± 21427e

Note: The different letters in the same column mean significant differences among different cropping systems ($P < 0.05$).

Table 6
The indexes of WEF_{RI} in different cropping systems.

Item	*ΔF-range*	I_w	I_e	WEF_{RI}
MW	0	1	1	2
MM	>40%	1.97	0.99	2.96
MR	>40%	0.74	0.81	1.55
MI	30%–40%	0.88	0.81	1.69
MO	<30%	0.83	1.09	1.92
MP	30%–40%	0.88	1.10	1.98
MS	>40%	1.85	0.93	2.78

Note: *ΔF-range* means the range of increase in the food supply of *i* cropping system relative to the MW control cropping system.

Compared to the MW control system, the food supply of the MI and MP systems had a reduction of 30%–40%. However, the groundwater irrigation input and non-renewable energy consumption of the MI system were 24.28% and 18.26% lower than those of the MW. The groundwater irrigation input and non-renewable energy consumption of the MP system were 28.46% and 42.68% lower than those of MW. The groundwater irrigation consumption and non-renewable energy inputs of MP system were lower than those of MI. From indexes of WEF_{RI} in Table 6, we could see that I_e was lower in the MI system (0.81) than in the MP system (1.10), and I_w in the MI system (0.88) had no difference from the MP system (0.88). Overall, WEF_{RI} in the MP system (1.98) was higher than that in the MI system (1.69). Consequently, when a 30%–40% reduction in food supply is acceptable, MP is recommended.

Compared to the MW control system, the food supply of the MO system had a reduction of less than 30%. The groundwater irrigation consumption and non-renewable energy consumption decreased over the MW system by 11.47% and 32.14% in MO. The WEF_{RI} of the MO system was 1.92. Although the WEF_{RI} of the MO system was not the highest among all of the cropping systems, the food supply was the highest except for the MW control system.

In general, the MM and MS system can be implemented to a certain extent in the NCP if the water shortage is severe. When a 30%–40% reduction in the food supply is acceptable, the MP system is recommended. The MO system is recommended when a less than 30% reduction in food supply capacity is acceptable.

4. Discussion

4.1. The importance of enhance the coordination among water, energy and food in the cropping systems

The approaches based on the WEF nexus to quantitatively assessing the cropping systems and providing proper strategies for the optimal systems to replace the wheat-maize cropping system at the field scale in the NCP. The demands of the water and energy of the cropping systems vary from each other, and their contributions to food security are also different. Taking food security and water resource shortage into account, we evaluate the WEF nexus of the different cropping systems at the field scale, which provide a theoretical reference for the optimization and distribution planning of local cropping systems.

In the NCP, the rapid increase in food production has been accompanied by a decline in the groundwater level, an increase in energy consumption and a deterioration in environmental quality (Wang et al., 2019). In this study, the wheat and maize double cropping system produced the highest food supply, but it also had the highest non-renewable energy inputs with fertilizer, diesel and electricity input as its main energy sources. These non-renewable energy sources were the main sources of greenhouse gas emissions from food production (Qiu et al., 2018; Mondani et al., 2017). Reducing agricultural energy input is critical for sustainable agriculture and climate change mitigation (Qiu et al., 2018).

The water resource inputs of this study, in addition to rainfall, were only dependent on extracted groundwater. The maximum annual groundwater extraction was 2790 m^3 ha^{-1} (the wheat and maize double cropping system) for food production during 2014–2019. Some studies have found that most of the groundwater depth reached 50 m in the NCP in 2014. According to the current rate of exploitation, the groundwater depth will continue to increase (Chen et al., 2020), which aggravates the energy consumption of irrigation extraction (Qiu et al., 2018). Moreover, high water and high fertilizer use in agricultural management causes a large amount of N leaching, which will pollute the groundwater (Wang et al., 2019).

In extremely water scarce areas, the government of the NCP advocated for monocropped maize system in recent years. Our study found that the groundwater input and non-renewable energy consumption of monocropped maize system were reduced by 73.95% and 48.01%, respectively, compared to wheat and maize double cropping system. The groundwater reduction was greatly alleviated, and the non-renewable energy consumption was reduced. Some studies also had similar findings that maize consumed fewer water resources and energy than wheat (Islam et al., 2019; Cui et al., 2018). Meanwhile, greenhouse gas emissions in farmland were also greatly reduced (Cui et al., 2019).

However, the NCP is an important food production area in China. In this study, the food supply of the monocropped maize system per hectare was 48.5% lower than that of the wheat-maize system. The large-scale implementation of monocropped maize system may pose a great threat to food security in the future. In the assessment of cropping systems, conventionally, only one aspect of water resources, energy and food security is considered, which is not conducive to sustainable agricultural development. In this study, the water, energy and food are regarded as a whole. While exploring their internal relationships, the problems of water resources, energy resources, environmental pollution and food security in agriculture are balanced to achieve a balance between the sustainable development of resources and food security. Enhancing the coordination among water, energy and food and improving the overall utilization efficiency are beneficial to regional agricultural sustainable development.

4.2. Providing suitable cropping systems theoretically according to the WEF_{RI}

Food security is important for agricultural development and social stability. Thus, this study provides theoretically suitable cropping systems to replace wheat-maize system with high water inputs and energy consumption. At the same time, the problem of food security is taken into account. According to the extent of the reduction of food supply capacity in comparison with wheat and maize double cropping system, the alternative cropping systems are divided into several ranges of above 40%, between 30% and 40% and below 30%. Within the scope of the dissimilar options, we chose optimized cropping systems of monocropped maize, intercropped maize and soybean, relay cropped maize with pea and maize with potato. Monocropped maize and intercropped maize and soybean had the largest WEF_{RI} indexes, compared with wheat and maize double cropping system, non-renewable energy consumption had been reduced by approximately 48% and groundwater consumption had been reduced by approximately 74%. Xu et al. (2020) also found a similar pattern in the NCP, where the water footprint of the monocropped maize was approximately 51% less than that of a wheat-maize rotation. However, soybean was a green fertilizer crop in the study, and there was no significant difference in the food supply of the two cropping systems, and they were low, only around 142573 MJ ha^{-1} and 152034 MJ ha^{-1}, which was reduced by approximately 50% compared with the wheat and maize double cropping system. However, some studies have found that monocropped maize can increase the yield and resource efficiency by 30%–50% in comprehensive optimization of sowing time, tillage method, sowing density and nutrient management (Yang et al., 2020; Singh et al., 2020). Moreover, soybean as a green manure contributed extra nitrogen to soil, increasing the content of organic matter and nitrogen in the land management (Zotarelli et al., 2012). Therefore, in areas with extreme water shortages, monocropped maize and intercropped maize and soybean are recommended. Pea is an important food and feed crop in China. In this study, relay cropped maize with pea, using groundwater inputs only, achieved 1996 m^3 ha^{-1}, and the non-renewable energy consumption was only 36121 MJ ha^{-1}, compared with wheat and maize double cropping system, which decreased by 28.46% and 48.30% respectively. Compared with the wheat and maize double system, the food supply capacity was reduced by 36.93%. However, peas are rich in protein of beans, which can improve the protein for both humans and animals (Felix et al., 2017). Moreover, leguminous nodules can be used for biological nitrogen fixation, and the symbiotic nitrogen fixation of leguminous crops can reach 75–150 kg ha^{-1} per year (Schipanski et al., 2010). In the intercropping combination of legumes and non-legumes, legumes can transfer some of their fixed nitrogen to non-legumes, which is beneficial to soil improvement and increasing the yields of non-legumes in the next crop (Yang, et al., 2018). Therefore, maize with pea relay cropping is a priority when a 30% to 40% reduction in the food supply is acceptable. Compared with wheat and maize double cropping system, in the food supply capacity, the decreasing amplitude is less than 30%, within the scope of the relay cropped maize with potato. The nutrition of potato is more abundant and comprehensive than that of grain, and its nutritional structure is more beneficial to human health.

In 2015, the Ministry of Agriculture put forward the strategy of potato becoming a staple food, which made the potatoes secondary to grain and ranked coarse grain to the fourth among the major grain in China (Lu, 2015). Water resources uses and energy consumption during potato growth are low. In this study, compared with wheat and maize double cropping system, the savings of groundwater and non-renewable energy were 11.47% and 32.14% respectively. Moreover, intercropping maize with potatoes could control soil erosion (Zero and Lima, 2005). Compared with wheat and maize double cropping system, the food supply capacity of the four cropping systems of monocropped maize and intercropped maize and soybean, and relay cropped maize with pea and maize with potato were reduced, but the usage of groundwater and non-renewable energy were also reduced. Besides, the fallow period of winter can effectively accumulate soil water (Cann et al., 2020). It can also effectively alleviate a series of ecological and geological environmental problems, such as the funnelling of the groundwater level in the NCP and the land subsidence caused by it.

4.3. The meaning and limitations of WEF_{RI}

The relative index method of this study can quantify absolute values of the indicators of water inputs, energy consumption and food outputs among treatment systems and the wheat-maize system (baseline). Fabiani et al. (2020) also used a percentage comparison of resource differences to assess the sustainability of different agronomic managements in wheat production in Italy, but a comprehensive quantitative index has not been given. El-Gafy (2017) and Gathala et al. (2020) studied the WEF index methods based only on the resource production efficiency of cropping systems. Of course, our studies all presented a comprehensive quantitative index to facilitate an intuitive integral comparison of water, energy and food for cropping systems (El-Gafy, 2017; Gathala et al., 2020).

The WEF_{RI} is successful in evaluating the WEF nexus of cropping systems. However, the method only gives the variability of indicators, expressed as percentages between the control group and the treatment group, and there are no answers to other WEF nexus questions, such as "one change makes all change" of water, energy and food in different cropping systems in the region. However, it is conducive for decision makers and stakeholders to adjust to a single aspect of more coordinated cropping systems of water, energy and food in the region being proposed further, and then a coordinated balanced development of regional resources and environment will be achieved. We also know that system dynamics is an important theory for building a scene simulation by assuming that one change affects the overall changes (Ravar et al., 2020). In addition, the methods of reducing water and energy consumption, in addition to changes in cropping systems, include adjusting water and fertilizer management (Xu et al., 2018), changing tillage systems (Reichert et al., 2020), etc. Therefore, it is worth considering establishing and applying a system dynamics simulation based on the WEF nexus at the field scale in the next study.

5. Conclusion

Water, energy resources and food security are closely related, and they are principal resources for agricultural production. The WEF_{RI} method of this study based on different percentage values of water, energy inputs and food output between treatment systems and the control system and the range of regional acceptable food supply reduction, can evaluate the water-energy-food nexus in cropping systems. This study use the WEF_{RI} method in the NCP to analyze the synergy between water, energy and food of seven cropping systems, and propose appropriate cropping systems for local decision-makers on the premise of ensuring food security. We concluded that monocropped maize and intercropped maize and soybean cropping systems to a certain extent can be implemented in areas with extreme water shortages in the NCP. When a 30%–40% reduction in food supply is acceptable, relay cropped maize with pea is recommended. Maize with potato relay cropping is recommended under the circumstance that a less than 30% reduction in food supply capacity is acceptable. The adjust method provides a theoretical basis for the local decision-makers to evaluate the cropping system, and facilitate the application of the water-energy-food nexus studies in the evaluation of cropping systems in the NCP. Consequently, the WEF_{RI} method would be as a useful approach to achieve higher agricultural resource adaptability and sustainability in the selection of cropping systems in specific regions.

CRediT authorship contribution statement

Jinna Li: Conceptualization, Data curation, Investigation, Methodology, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Jixiao Cui:** Methodology, Formal analysis, Validation, Data curation, Writing - review & editing. **Peng Sui:** Methodology, Formal analysis, Resources, Supervision. **Shunnian Yue:** Investigation, Data curation. **Jia Yang:** Investigation, Data curation. **Ziqing Lv:** Investigation, Data curation. **Dong Wang:** Investigation, Data curation. **Xingqiong Chen:** Investigation, Data curation. **Beibei Sun:** Investigation, Data curation. **Mengmeng Ran:** Investigation, Data curation. **Yuanquan Chen:** Methodology, Formal analysis, Funding acquisition, Resources, Supervision, Validation.

Declaration of Competing Interest

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

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