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Crop switching could be a win-win solution for improving both the productivity and sustainability in a typical dryland farming region-Loess Plateau, China

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ABSTRACT

Increasing crop yield and reducing environmental impacts are conductive to regional sustainable food production, while integrated evaluation of them is still lacking. To fill this gap, a new systematic analysis method was developed to quantify crop yield, economic input and environment impact of farmland. Taking the farmland ecosystems of Loess Plateau (LP) in China during 2014–2018 as a case, this new systematic analysis method was applied to quantify the ecological environment, systematic sustainability, and socioeconomic characteristics (indicators) of the farmland ecosystems in dry farming. Then, by exploring the relationships of these indicators and combining with crop switching analysis, the relatively unsustainable counties in farming and the improving potential of sustainable crop production was clarified, respectively. Several interesting results were explored. (1) The counties with the farmland of grey-water footprints exceeding 500 m^3/t or soil erosion empowers exceeding 1.5E+12 sej/ha could be categorized as the relatively unsustainable counties in farming. (2) Maize and sorghum showed superior performance in terms of both environmental sustainability and crop productivity, and had promotion advantages in LP. (3) Crop switching could reduce grey water footprint and soil erosion of farmland by up to 27.41% and 35.14% respectively, and increase emergy sustainability index and crop yield by up to 10.35% and 19.90% respectively. The integrated systematic analysis method and crop switching method has high application value for regional sustainable crop production, especially for dryland regions with fragile ecological environment and prominent food demand-supply conflict.

1. Introduction

With the frequent occurrence of natural disasters such as floods, droughts, volcanic eruptions, and locust plagues caused by climate change, the global food security is currently facing severe challenges according to the Global Report on Food Crises in 2020, especially for the dryland regions, such as West Africa (Aune et al., 2019), the US Great Plains (Ghimire et al., 2018), southwestern Australia (Harper et al., 2017), and northern China (Zhu et al., 2021). Additionally, the worldwide outbreak of COVID-19 has also caused severe impacts on the global economy and trade, and thus on global food security (Gong et al., 2021). Sustainably meeting food demands is one of humanity's grand challenges at both the global and regional levels, especially for dryland regions with high population density and high food demand pressure. There is therefore an urgent need to increase domestic and sustainable food production to address food security issues.

Sustainably improving crop productivity on existing farmlands has been given a high priority (Licker et al., 2010), especially for dryland farming with declining soil fertility status and increasing climatic stresses (Ghimire et al., 2018). Studies have shown that the utilization of agricultural management measures, including conservation agriculture (e.g., no tillage) and planting structure adjustment (e.g., crop switching) could effectively solve this problem. For example, Mueller et al. (2012) reported that the global production of most crops could increase 45%–

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70% in current agricultural lands by improving agricultural management practices. With crop switching (also called crop redistribution), the yields of six crops in the United States increased significantly compared to the original situation (Rising and Devineni, 2020). On the other hand, due to the excessive use of chemical fertilizers, pesticides, and modern machinery, most of the world's cultivated land is currently suffering from soil erosion, soil organic matter loss and soil structure destruction (Borrelli et al., 2017). The average global nitrogen use efficiency in crop production has decreased to 0.42–0.47 (Zhang et al., 2015), and the emission and leaching of the unutilized nitrogen have posed a notable threat to human and ecosystem health (Zhang, 2017). In response to these issues, there is an urgent need for solutions that can simultaneously increase crop yields and reduce the environmental impacts on the existing farmland.

In general, crop growth is affected by a combination of soil, climate, irrigation, crop management, etc. (Chenu et al., 2017). Based on emergy and limiting factor theories, the emergy matching theory believes that when purchased inputs to a production system are reasonably matched with its local environmental inputs, the economic investment can be efficiently utilized. As a result, the production efficiency of the system can be maximized (Odum, 1996). For example, when the purchased inputs of a farmland (e.g., fertilizers and pesticides) are matched with the inputs of natural resources (e.g., precipitation), the purchased inputs can be efficiently used (Giannetti et al., 2011). Although excessive purchased resources could further increase crop yields, they are not only inefficient, but might also lead to a decline in environment (e.g., soil quality) (Mueller et al., 2012). It is essential to explore the reasonable match relationship between local and purchased inputs to farmland, especially in ecologically fragile dryland regions.

As a biophysical donor-side valuation method, emergy evaluation can quantitatively synthesize different material and energy inputs, by converting them into the same unit of solar emergy joules (sej) (Ghisellini et al., 2014). Furthermore, the emergy system diagram model can clarify the network processes of emergy flows, utilizations, and transformations in a system, thereby helping to understand the structures and functions from a systematic view (Odum, 1996). By developing an emergy system model, it is possible to better understand the resource utilization efficiency and environmental impacts of the farmland.

By integrating an emergy system model and a crop growth model, this study developed a new systematic analysis method combing crop production, economic inputs, and environmental impacts of farmland ecosystems (Fig. 1). The Loess Plateau (LP) of China was selected as an example of dryland region to conduct our analysis, considering its extremely prominent contradiction of food demand-supply (Fu et al., 2017). The ecological environment in the LP is relatively fragile, with obvious water shortages and serious soil erosion (Yang et al., 2018) and farmland pollution (Wu et al., 2016). Meanwhile, the population density in this region is high, i.e., 203.13 people/km^2 in 2020, accompanied by a high regional food demand pressure and a tough food security problem. It is expected that the grain demand in Gansu Province of LP would be 9.38E+6 t/yr in 2030, while the regional grain production would only be 6.45E+6 t/yr. That is, the self-sufficiency ratio of grain in this region would be only 68.89% (Fang et al., 2015). Exploring a solution for the sustainable yield increase is urgently needed for the sustainable development of the LP, which would also be valuable for other dryland regions with tough food demand pressure, e.g., some countries in Africa.

An emergy system model of farmland ecosystems (Fig. 1c) in LP was established. Considering the above issues (i.e., limited precipitation and serious soil erosion vs. high food demand pressure), six indicators related to ecological environment, systematic sustainability, and social economy were adopted to quantify the characteristics of farmland ecosystems. The farmlands of seven major grain crops, including maize, wheat (including spring wheat and winter wheat), rice, sorghum, soybean, millet, and potato, were selected to represent the regional farmland ecosystem. Because the sum of their areas account for more than 90% of the total harvest area in LP (National Bureau of Statistics, 2016). By exploring the relationships between the six indicators and using scenario analysis of crop switching at county scale, this study attempts to (1) clarify the relationships among resource utilization structure, environmental impacts, and ecological economic sustainability of the farmland ecosystems. (2) Clarifying the potential of the crop switching in improving the sustainable yield of farmland in dryland regions with higher food demand pressure.

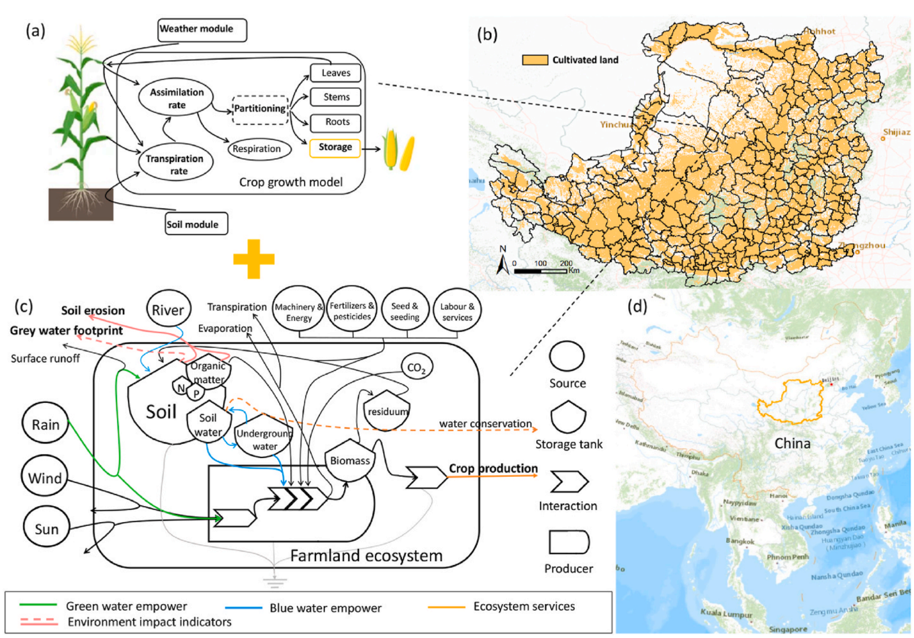

Fig. 1. The systematic analysis method integrating a crop growth model (a) and an emergy system model (c) in the Loess Plateau, China. (b) refers to the cultivated land in the Loess Plateau, China and (d) refers to the location of Loess Plateau, China.

2. Materials and methods

2.1. Study area

The LP covers an area of 62.4 × 10^4 km^2 and includes 7 administrative provinces in northwestern China, including Shanxi, western Henan, northern Shaanxi, middle and eastern Gansu, central-southern Ningxia, northeastern Qinghai, and Inner Mongolia (Fig. 1b and 1d). This region is mainly dominated by a semi-arid continental monsoon climate and the annual precipitation is commonly less than 500 mm, varying from less than 300 mm in the northwest to 700 mm in the southeast (Fu et al., 2017). The 400 mm annual precipitation isopleth has divided this region into two distinct areas: southeast and northwest (Tsunekawa et al., 2014), with about 60 counties in the northwest region and 230 counties in the southeast region (Fig. S1).

For a long time, the LP is notorious for its severe drought, severe soil erosion, sparse vegetation, large population, low agricultural productivity, and poverty of farmers (Fu et al., 2017), making it one of the world's major ecologically fragile regions. Although the crop yield has increased through the application of chemical fertilizers, pesticides, machinery, and engineering, etc. (Shi et al., 2020), it is still hard to satisfy the regional food demand (Fang et al., 2015). In addition, the overuse of chemical fertilizers and pesticides has also caused a decline in soil quality, making the farmland unsustainable (Zhou et al., 2013). How to achieve the sustainable yield increase is an urgent problem for the governments and farmers.

2.2. Crop growth simulation

The main framework of this study was shown in Fig. 2. First, a crop growth model was developed to evaluate the crop yields, because some yield data of the selected crops in LP were missing and there were potential misreporting problems for the yield data at lower administration levels in China (Liu et al., 2020). A world food studies model (WOFOST) was employed considering its three advantages: (1) as part of the operational crop yield forecasting systems, WOFOST has been applied for 25 years, and the prediction accuracy was relatively high (Wit de et al., 2019). (2) Over 22 crops (including the seven main crops in LP) have been simulated by this model (Huang et al., 2017; Ceglar et al., 2019; Jiang et al., 2020), and the crop parameters were available online (https://github.com/ajwdewit/WOFOST_crop_parameters). (3) the WOFOST can be implemented on the spatial scale (Wit de et al., 2019).

WOFOST is a simulation model for quantitative analysis of the growth and production of annual field crops. In this model, the crop growth is simulated based on the eco-physiological progresses such as growth and phenological development. The major modules in WOFOST include phenological development, CO_2 assimilation, leaf development and light interception, transpiration, respiration, portioning of assimilates to various organs, dry matter formation, and soil water balance (Wit de et al., 2019). The moisture content in the root zone follows daily calculation of the soil water balance. The crop production in WOFOST can be distinguished into three levels: potential, limited, and reduced production (Wit de et al., 2020). The potential production is determined by the crop's response to temperature and solar radiation, with soil moisture being assumed as continuous. The limited production also

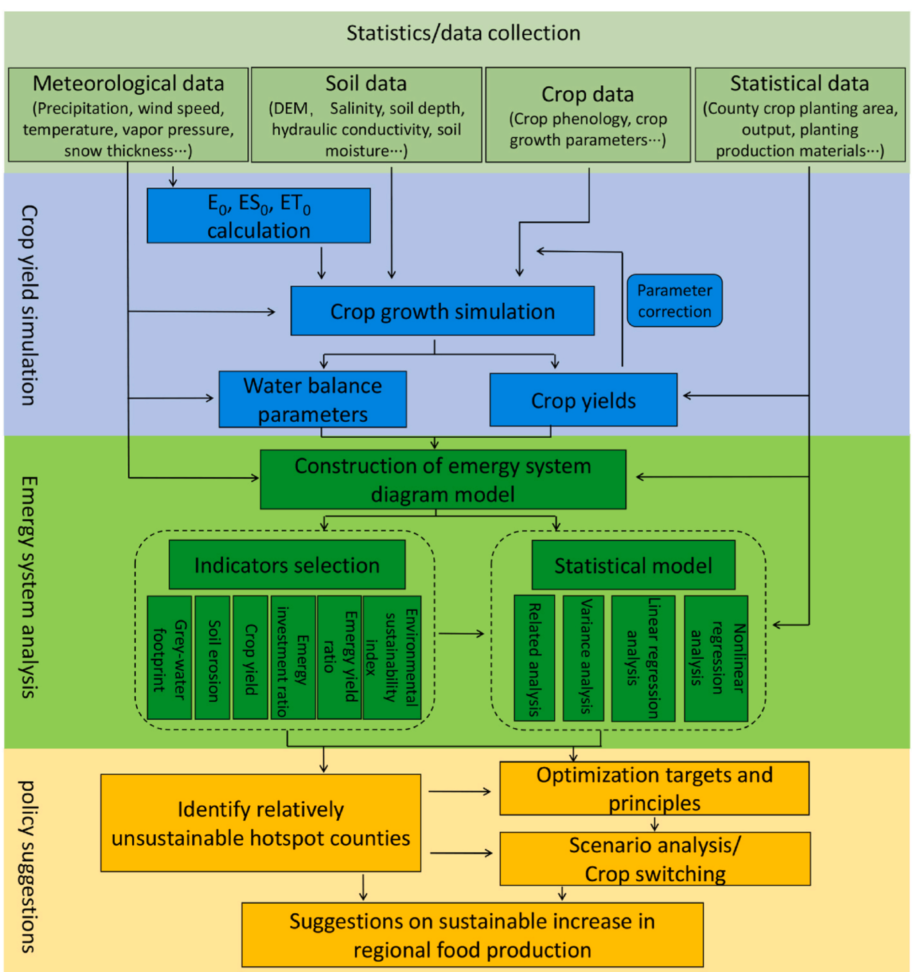

Fig. 2. Flowchart of procedure used in this study.

considers the effect of availability of water and plant nutrients. The soil water balance in water-limited production situation is applied to a freely draining soil, where the groundwater has a weak influence on soil moisture content in the rooting zone. The reduced production is influenced by many biotic factors such as weeds, pests, and diseases.

In this study, the potential and water-limited production of WOFOST were used to represent the yield of the irrigated and rain-fed farmlands, respectively. Because that the soil water availability was reported as one of the main stress factors for crop growth in LP (Jin et al., 2018). The effects of insects and diseases on crop yield were not considered, since no significant outbreaks of insects or diseases were reported in LP in 2014–2018. Since the spatial distributions of all selected crops were mapped in earlier years (e.g., in 2010 and 2000), it was first corrected by the land use patterns in 2015 and then calibrated again for more accuracy based on the statistics of crop harvest areas in each county from 2014 to 2018 (Table S1). The simulation progress of crop yield was first conducted at a $0.1^{\circ} \times 0.1^{\circ}$ spatial scale, and then aggregated from the grid scale to the county scale for further analysis. It is worth noting that before the progress of aggregation, the simulated results were first weighted in each grid cell by the ratio between irrigated or rain-fed areas to all harvest areas and then summed. The sources/references of the required data for crop yield simulation, including the weather data, soil data, crop area and growth parameter data and management parameters, were shown in Table S1. The crop parameters were first collected from the WOFOST database (https://github.com/ajwdewit/WOFOST_crop_parameters); and then adjusted according to the related crop parameters calibrated in LP (Huang et al., 2017) or in China (Cheng et al., 2020; Jiang et al., 2020). The crop parameters were finally calibrated for more accuracy according to some common indicators (e.g., Pearson correlation coefficient, mean absolute error, root mean square error). The calibrated results were shown in Figs. S2 and S3.

2.3. Emergy system model analysis

2.3.1. Emergy synthesis and diagram model

Emergy refers to the available energy need, directly or indirectly, through input pathways to make a product or service (Odum, 1996). Theoretically, all products and services can be converted into a unified unit of solar energy joules (sej) by multiplying by the unit emergy values (UEVs). The calculation as follows:

$$E_m = \sum_i (Tr_i \times Ex_i) \quad \mathrm{i} = 1, 2, 3 \ldots, \mathrm{n} \tag{1}$$

$$Tr_i = U_i / Ex_i \tag{2}$$

E_m refers to the emergy of the m service or product; Ex_i refers to the i_{th} input flow making the m service or product; Tr_i refers to the UEV of the i_{th} input; U_i refers to the emergy of the i_{th} input. By defining the UEV of solar energy as 1 sej/J, various services and products can be uniformly quantified (Brown and Ulgiati, 2018). Empower, defined as the emergy flow into a system per unit time, is an indicator of the resource utilization intensity of the system. In this study, the time scale was set as the entire growth cycle of each selected crop.

An important step in emergy evaluation is to set up a system diagram of the system under study, determining all key aspects of the input and output, their relationships, and categories (Odum, 1996). Fig. 1c presented the emergy system diagram model of the crop planting system. It showed the system boundary, the sources of natural and economic resources, and the utilization and conversion processes/flows of these resources in the system boundary and between intra storages of the system, and finally flows out the system boundary as economic yield or thermal dissipation. For further analysis, the resources were divided into three categories: R referred to the local renewable resources, N referred to the local nonrenewable resources, and F referred to the purchased inputs including products (P) and services (S).

In this study, the R included rain, wind and sun, which were collected from the weather data (http://www.geodata.cn/) at grid scale (Fig. 1, Table S1). The N equaled to soil erosion empower (SEE), which was calculated by Equation (3) at grid scale. The P included fertilizers, pesticides, diesel, petrol, electricity, seeds, and labor, which were mainly collected from the statistical yearbook and bulletin in China in 2014–2018 at county scale (Fig. 1, Table S1); The P also included irrigating water, which was simulated from the WOFOST model at grid scale. The S mainly included lease operation cost, machinery operation cost, tool and material costs, repair and maintenance costs, and the depreciation of fixed assets, which were also collected from the statistical yearbook and bulletin in China in 2014–2018 at county scale (Table S1). The farmland ecosystem output in this study was mainly crop yield, which was collected from the statistical yearbook and bulletin in China in 2014–2018 at county scale and from the WOFOST model at grid scale.

2.3.2. Indicator selection and calculation

Considering the specific environmental issues suffered in the LP (Fu et al., 2017), an emergy system model of the farmland ecosystem was developed (Fig. 1c). The data of the inputs, intra flows, and outputs of the emergy system model were collected from publications or peer reviewed papers, statistics, and the simulated results of WOFOST (the references are given in Tables S1 and S2). The UEV of each element being coded in this model was given in Table S2. SEE and grey water footprint (GWF) were the specific ecological environmental indicators in this study. Only the influence of nitrogen fertilizer was considered for GWF, because it was the main fertilizer used in LP (National Bureau of Statistics, 2016), and the GWF was mainly caused by chemical fertilizer utilization (Zhou et al., 2013). The calculation of SEE (sej/ha) and GWF (m^3/t) as follows:

$$SEE = SR \times EPPSR \tag{3}$$

$$GWF = \frac{(\alpha \times AR)/(C_{max} - C_{nat})}{CY} \tag{4}$$

SR refers to the surface runoff per unit area of the crop planting system in the whole crop growth cycle; EPPSR refers to the water erosive production potential per surface runoff, which was obtained from Han et al. (2021); α refers to the leaching rate (the ratio between the pollutants entering the water body to the total chemical substance application); AR refers to the fertilizer application amount per hectare (kg/ha) per crop growth cycle; $C_{\max}$ refers to the maximum acceptable concentration for the pollutant, C_{nat} refers to the natural concentration of the pollutant in the receiving water body; CY refers to the crop yield (t/ha) per hector per crop growth cycle. The values of $C_{\max}$ and C_{nat} refer to Hoekstra et al. (2011).

Some emergy indices were also employed to quantify the ecological economic performances of the farmland ecosystems, i.e., emergy investment ratio (EIR, Amiri et al., 2019), emergy yield ratio (EYR, Odum, 1996), environment loading ratio (ELR), and emergy sustainability index (ESI) (Brown and Ulgiati, 1997). The EIR is defined as the ratio of the purchased emergy inputs to the environmental emergy inputs. The smaller the ratio is, the lower the economic cost, and the higher the economic competitiveness and prosperity of the system, while a too low value indicates that the system is underdeveloped (Zhang et al., 2016).

$$EIR = \frac{P + S}{R + N} \tag{5}$$

EYR is calculated as the system's emergy output divided by the purchased emergy inputs, reflecting the ratio of efficiency of purchased input in exploiting local resources (Odum, 1996). The higher the ratio is, the higher the efficiency of the purchased inputs to the system.

$$EYR = \frac{Y \times \mathrm{UEV}}{P + S} \tag{6}$$

ELR is defined as the ratio of total nonrenewable emergy inputs to the total renewable emergy inputs to a system. It is an indicator of the pressure of the systematic process on the local ecosystem (Brown and Ulgiati, 1997). The lower the ratio is, the lower the environmental pressure is.

$$ELR = \frac{F + N}{R} \tag{7}$$

ESI is calculated as the ratio of EYR to ELR (Brown and Ulgiati, 1997). This indicator takes both ecological and economic compatibility into account. The larger the value is, the higher the sustainability of a system.

$$ESI = \frac{EYR}{ELR} \tag{8}$$

Six indicators were selected to evaluate the performance of the farmland ecosystem from three aspects, i.e., the ecological environmental aspect (GWF and SEE), systematic sustainability aspect (ESI) and social economic aspect (EIR, EYR and CY). All indicator calculations were based on the growth cycle of crops, and the crops selected were only planted once per year.

2.4. Statistical analysis

To reduce the impacts of inter-annual differences on the results, the values of all indicators in 2014–2018 were averaged before statistical analysis. Correlation analysis, simple linear regression and nonlinear regression were used to explore the relationships between the ecological environment, systematic sustainability, socioeconomic indicators and other related indicators (e.g., irrigation water, crop water consumption and precipitation). The progress of the statistical analysis was conducted using the "raster", "dplyr", "rgdal", "reshape2" and other packages in the R 3.6.1 environment (Wickham, 2007; Bivand et al., 2013).

2.5. Optimization analysis

It was expected that with the increase in economic inputs (e.g., the increase in the utilization of fertilization and machinery), the GWF and SEE would first increase slowly and then rapidly when these inputs increased to some degree, while the increasing trends of EIR, EYR, CY and ESI were the opposite. By exploring the inflection points of the curves between the ecological environmental indicators (GWF and SEE), systematic sustainable indicator (ESI), and social economic indicators (EIR, EYR, and CY), the critical values of GWF and SEE can be identified. The counties with high GWF and SEE values greater than their critical values can be defined as relatively unsustainable counties in farming. The optimization priority for the unsustainable counties was first given to reduce the environmental impacts (e.g., decreasing the GWF and SEE), and then to increase the crop yield. For the other counties with relatively sustainable farmland ecosystems, the optimization priority was given to improve the crop yield, with the environmental impacts (i.e., GWF and SEE) being controlled to be less than the related critical values.

A scenario analysis was applied to quantify the potential of crop switching in improving the sustainable yield of farmland. Crop switching was considered a possible spatial optimization strategy for maximizing crop profits following Rising and Devineni (2020). It was performed by shifting the planting areas of all crops in each county to decrease the environmental impacts and increase crop yield according to some optimized principles, which was discussed in the Results. Winter wheat was excluded from crop switching, considering that its cultivation season did not coincide with the other crops.

It is worth noting that the crop switching in each county was based on three basic hypotheses: (1) the cultivated area in each county was constant, (2) only crops that had already been planted in the county were suitable for crop switching, and (3) the planting inputs for each crop in each county remained unchanged. Four crop switching scenarios were analyzed in this study: 25% (scenario 1), 50% (scenario 2), 75% (scenario 3), and 100% (scenario 4) of the existing farmland was involved in crop switching.

3. Results

3.1. Distributions of the environment and economic characteristics

The distribution maps of the six selected indicators were shown in Figs. S4–S8. High GWFs were mainly distributed in the central and southern regions of the LP (Fig. S4a), while high values of SEE, EYR and CY were mainly distributed in the northern and eastern regions (Fig. S4b, S4e-f). Low EIRs were mainly distributed in the eastern regions of the LP. (Fig. S4d). Finally, high ESIs were mainly distributed in the northern LP (Fig. S4c).

3.2. Correlations among the six indicators

It was found that the relationships between EIR and EYR, EIR and ESI, EYR and SEE, EIR GWF, and SEE and CY were different in the northwest LP (prec <400 mm) and the southeast LP (prec >400 mm) (Figs. S9–S11). It seemed that the GWF and SEE had no significant correlations with EIR, EYR, ESI and CY in prec <400 mm region, while they had nonlinear correlations with these indicators in prec >400 mm region (Figs. S9b–c). Therefore, it was necessary to analyze these indicators in the two regions separately.

CY showed positive correlations with water consumption, EYR, and ESI in both regions with prec <400 mm and prec >400 mm (Fig. 3a–c). Similar results were also found between water consumption and EYR and ESI (Fig. 3d and e). The EIR showed a negative relationship with precipitation and a positive correlation with irrigation water in both regions with prec <400 mm and prec >400 mm, while the R^2 of the EIR and irrigation was low in the prec >400 mm region ($R^2 = 0.05$) (Fig. 5a and b). The relationships of EIR and water consumption were positive in the prec <400 mm region and negative in prec >400 mm region (Fig. 3h).

At the prec >400 mm region in LP, the GWF had nonlinear correlations with the two socioeconomic and sustainable indicators (EIR and ESI, Fig. 6a and b). With the increase in GWF, the EIR first increased rapidly and then increased slowly after the GWF reached approximately 500 m^3/t. Similarly, with the increase in GWF, the ESI first decreased sharply and then decreased slowly after the GWF reached approximately 500 m^3/t. The SEE had no significant correlations with ESI and EIR but nonlinear relationships with CY and EYR (Fig. 4c and d). With the increase in SEE, both CY and EYR first increased sharply and then increased slowly and even trended toward stability after the SEE reached approximately 1.5E+12 sej/ha.

3.3. Optimization principles, strategies, and results

Based on the above correlation analysis results, the counties with GWF >500 m^3/t or SEE >1.5E+12 sej/ha were determined to be relatively unsustainable counties in the region with prec >400 mm in LP (Fig. 5). The counties with relatively unsustainable farmland ecosystems in prec <400 mm region were also defined following the same principle as those in prec >400 mm region. Because the ecological environment indicators (GWF and SEE) were not significantly correlated with the sustainable indicator (ESI) and the social economic indicators (EIR, EYR and CY) in this region. It was interesting that the determined unsustainable counties in prec <400 mm region were coincidently the counties with abnormal GWF or SEE values (i.e., the outliers of the boxplots in Fig. 3i and j).

According to the optimization principles of farmland ecosystems in counties on the LP (Table 1), the number of counties with high GWF and SEE decreased, while counties with high CY, EYR and ESI increased (Figs. 6 and S12). Results showed that the harvest area of maize and

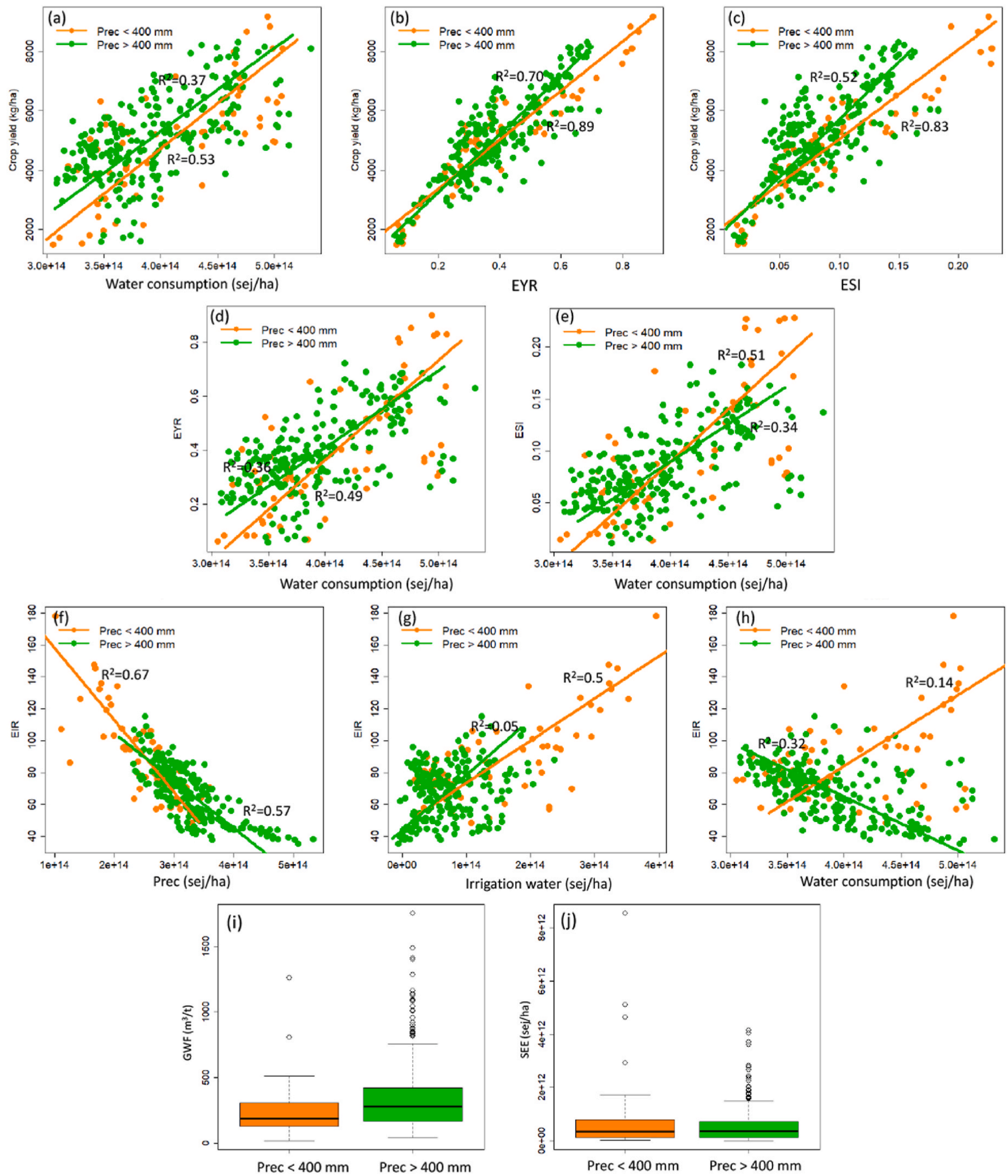

Fig. 3. The simple linear regression analysis between different indictors and the boxplots of GWF and SEE. (a, b, c) refer to the relationships of crop yield with water consumption, EYR and ESI, respectively. (c, d) refer to the relationships of water consumption with EYR and ESI. (f, g, h) refer to the relationships of EIR with precipitation, irrigation water and water consumption, respectively. (i, j) refer to the boxplots of GWF and SEE. Water consumption of crop planting system refers to the sum of precipitation and irrigation water in each growth cycle of the crop. EYR, ESI, EIR, GWF, and SEE refer to emergy yield ratio, emergy sustainability index, emergy investment ratio, grey water footprint, and soil erosion empower, respectively.

sorghum gradually increased from scenario 1 to scenario 4. In scenario 4, the harvest areas of maize and sorghum increased by 25.74% and 3.87% compared to their original harvest areas, respectively. As a result, the CY, EYR, and ESI increased by 19.90%, 10.04%, and 10.35%, respectively, while the GWF and SEE decreased by 27.41% and 35.14%, respectively (Fig. 7).

4. Discussion

How to increase crop yield and reduce environmental impacts simultaneously in ecologically fragile dryland farming is conducive to achieving a sustainable increase in regional food production. Although crop switching has been used as a key strategy for agriculture to adapt to climate change and to increase crop yield (Rising and Devineni, 2020), this method seldom took economic and environmental impacts into account. Taking the LP as an example of dryland regions, by integrating an emergy system model and a crop growth model, the newly developed systematic analysis method could incorporate crop production with socioeconomic and environmental impacts. It therefore gives us an opportunity to explore the potential matching relationships between these

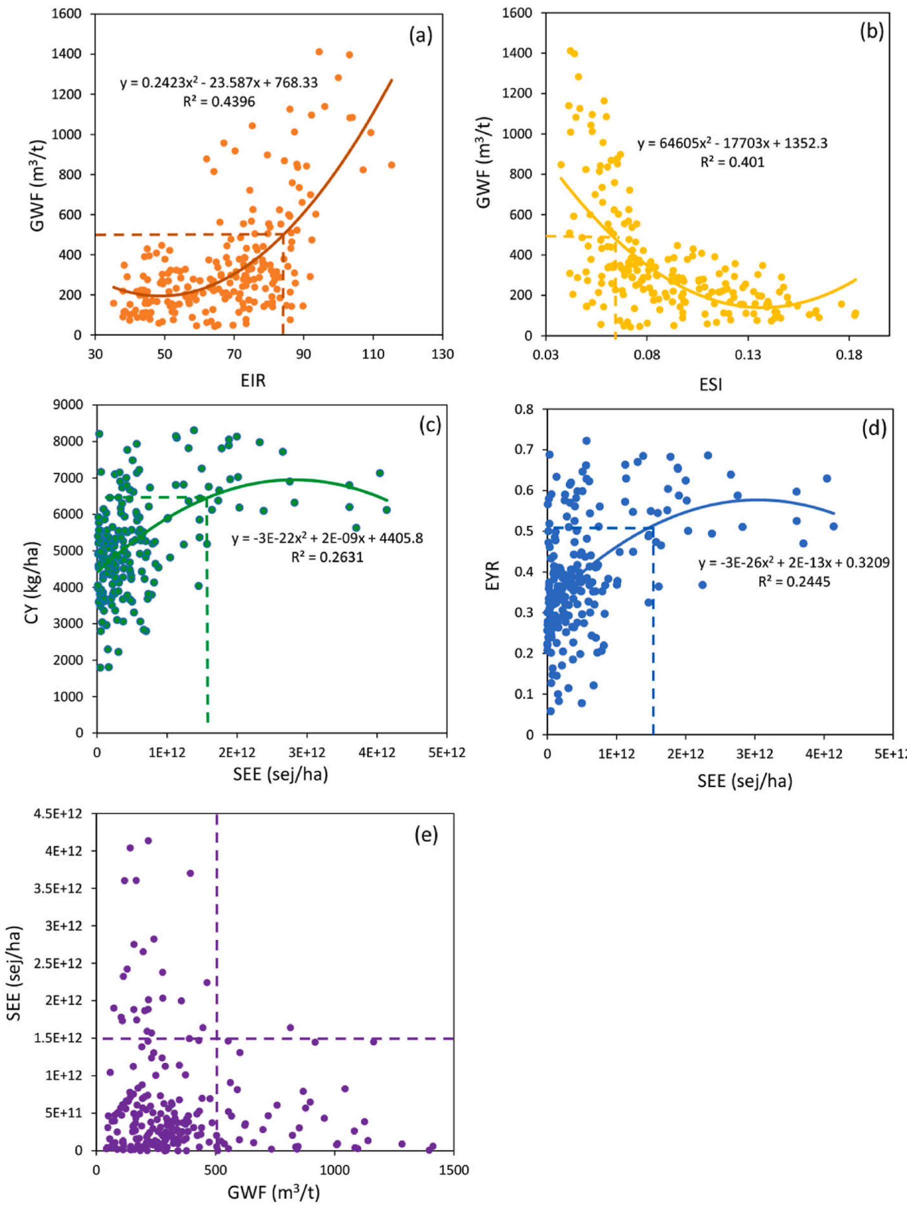

Fig. 4. The non-linear regression analysis between various indictors in prec >400 mm regions in Loess Plateau, China. (a, b, c, d) refer to the non-linear relationships between GWF and EIR, GWF and ESI, CY and SEE, EYR and SEE, respectively. (e) refer to the relationship between SEE and GWF. EIR, EYR, ESI, GWF, SEE, and CY refer to emergy investment ratio, emergy yield ratio, emergy sustainability index, grey water footprint, soil erosion empower, and crop yield, respectively.

indicators, which are useful to clarify the ecological economic characteristics of the farmland ecosystems. For the sake of both food security and environmental sustainability, this work established a new systematic analysis method for sustainable food production in dryland farming.

4.1. *Usability and dependability of the systematic analysis method*

It was noted that the optimization of farmland ecosystems in LP in this study did not consider the food preferences of the local people and some economic factors, such as crop prices and global trade. However, the analysis processes were reasonable to some extent considering the tough food demand-supply conflict in LP and China, and the main target this study was to assess the performance of the developed systematic analysis method in achieving a sustainable increase in regional food production. In addition, the selected crops were the main regional grains that were subject to their prices under government macroeconomic control.

It is difficult to use only one simple technique to achieve a sustainable increase in regional food production at global scale, because the issues in different places are always different. For example, although some conservation agriculture techniques (i.e., no tillage) have been utilized around the world (Garnett et al., 2013), Corbeels et al. (2020) reported that conservation agriculture was not a good technique for African smallholder farmers to overcome low crop yield and food insecurity. By using the systematic analysis method developed in this study, it was possible to identify unsustainable grain production regions and its main issues, so that some corresponding optimization strategies, e.g., crop switching, could be utilized.

This study confirmed that relatively unsustainable counties could be identified by exploring the relationships between economic inputs, environmental impacts, and system outputs. The crop switching was also verified as a win-win solution for both increasing the crop yield and decreasing the environmental impacts. For example, although the farmland in LP has decreased approximately 13.55% since 1999 after the launch of Grain for Green Project (Han et al., 2021), there was still a potential for increasing the crop yield to 103.65% of that before the

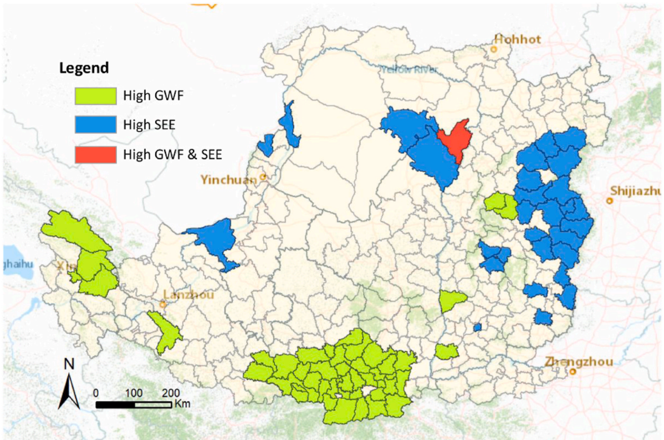

Fig. 5. The counties with relative unsustainable farmland ecosystem. GWF and SEE refer to grey water footprint and soil erosion empower.

project, under the premise of a sustainable environment of the existing farmland. Therefore, from the food security and environmental sustainability aspects, the newly systematic analysis method proposed in this study, has high application value in dryland areas where the conflicts of food demand and supplementation are prominent.

4.2. Identification of counties with relatively unsustainable farmland ecosystems

In this study, the water consumption of farmland ecosystems was calculated by the sum of precipitation and irrigation water, and it was found to have positive linear relationships with CY, EYR and ESI in both regions with prec <400 mm and prec >400 mm (Fig. 3). That is, the efficiency of economic resource/service inputs in both regions increased with the increase of water availability. The positive relationship between water consumption and CY also indicated that water availability has a significant effect on the productivity of farmland ecosystems. Based on a meta-analysis of 39 studies in smallholder farms and experimental stations on the LP, Zhang et al. (2013) also reported that grain yield can be improved through agricultural management, which can increase soil water availability, e.g., straw mulching and plastic film mulching.

Many studies have evaluated the GWF and SEE of farmland ecosystems on the LP (Zhuo et al., 2016; Liu et al., 2019; Tao et al., 2020), but studies assessing the relationships between these environmental indicators and economic and sustainable indicators on a regional scale

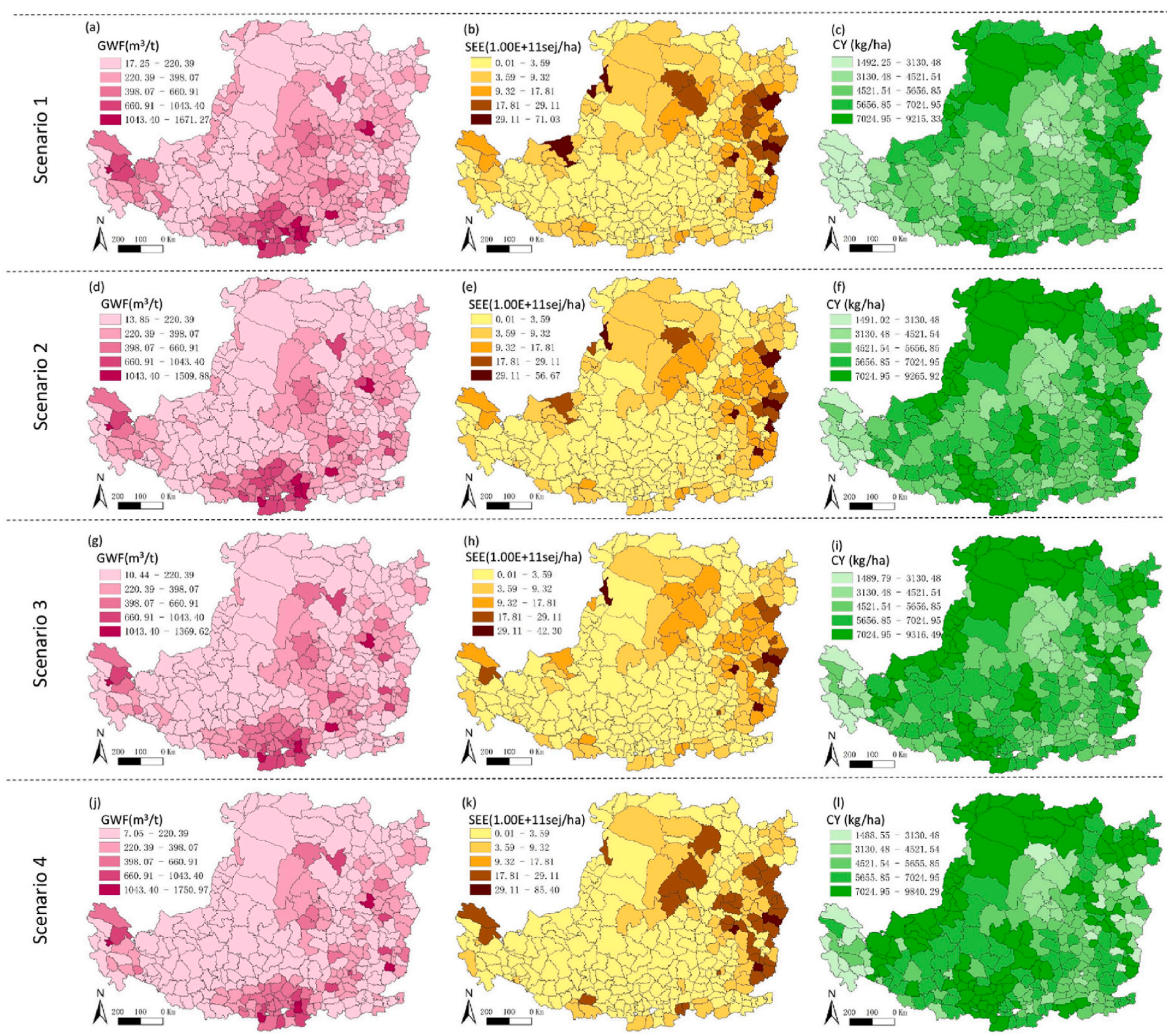

Fig. 6. Optimization results of different optimization scenarios using crop switching. (a, b, c) refer to the distribution maps of GWF, SEE and CY in Scenario 1. (d, e, f) refer to the distribution maps of GWF, SEE and CY in Scenario 2. (g, h, i) refer to the distribution maps of GWF, SEE and CY in Scenario 3. (j, k, l) refer to the distribution maps of GWF, SEE and CY in Scenario 4. GWF, SEE, and CY refer to grey water footprint, soil erosion empower, and crop yield, respectively.

Table 1
The optimization targets and principles of crop switching in the existing farmland.

Annual average precipitation	Specific counties	Targets of optimization	Principles of crop switching (On the basis of CY increase)
Prec <400 mm (Arid and semi-arid region)	Relative sustainable counties	Improve the water use efficiency (i.e., improve water productivity)	Keep the GWF less than 500 m^3/t; Keep the SEE less than 1.5E+12 sej/ha.
	Relative unsustainable counties (Abnormal values of GWF or SEE)	Optimize the input method of external resources and reduce the environmental impact	Reduce the GWF of the farmland; Reduce the SEE of the farmland.
Prec >400 mm (Wet and semi-humid region)	Relative sustainable counties	Improve the total grain production of the farmland ecosystem	Keep the GWF less than 500 m^3/t; Keep the SEE less than 1.5E+12 sej/ha.
	Relative unsustainable counties (GWF >500 m^3/t, SEE >1.5E+12 sej/ha)	Reduce the input of external resources; and reduce the environmental impact	Reduce the GWF of the farmland; Reduce the SEE of the farmland.

Notes: GWF, SEE, and CY refer to grey water footprint, soil erosion empower, and crop yield, respectively.

were rare, although sustainability is obviously affected by their integration. In this study, the GWF and SEE were found have a nonlinear relationship with EIR, ESI, EYR and CY (Fig. 3) in the prec >400 mm region in LP. It was therefore possible to explore the reasonable matching relationships between the socioeconomic and sustainable characteristics and the environmental characteristics. We found that when GWF >500 m^3/t, although the increase in EIR could improve CY, it had a severe effect on the environment (i.e., the GWF increased sharply) (Fig. 4a and 4b). In addition, although SEE was found to have positive relationships with CY and EYR, when SEE >1.5E+12 sej/ha, CY and EYR increased slightly and even stabilized. From the environmental impact aspect, the relative unsustainability threshold of farmland ecosystems in prec >400 mm region, therefore, can be defined as GWF >500 m^3/t and SEE >1.5E+12 sej/ha. The counties with relatively unsustainable farmland ecosystem in prec <400 mm region were defined following the same principle as those in the prec >400 mm region. Because no significant relationships were found between these ecological environment, systematic sustainability, and socioeconomic indicators in this region. An interesting finding was that the counties with relatively unsustainable farmland ecosystems in prec <400 mm region were coincidently the counties with outliers in the boxplots of GWF or SEE values (Fig. 3i and j). The relatively unsustainable threshold of GWF and SEE at the prec >400 mm region, therefore, can be expanded to the whole LP regions.

4.3. Optimization strategies for dryland farming ecosystems

An interesting finding was that high GWFs were generally associated with low SEEs, while high SEEs were generally associated with low GWFs in the prec >400 mm region (Fig. 4e). Meanwhile, we also found that nitrogen fertilizer has a positive relationship with economic inputs (Fig. S9). This indicated that the relative high purchased inputs (i.e., EIR), companied by the overutilization of nitrogen fertilizers, might increase the environment pollution risk (i.e., GWF), and finally lead to a decrease of farmland sustainability (i.e., ESI) (Fig. 4a, 4b, 4e).

As a ‘bridge between environment and economy’, emergy theory and evaluation methods were applied for multiscale ecological economic evaluations in the past four decades (Lan et al., 2002; Lu et al., 2022). A suite of emergy indices were widely applied in previous studies as objective indices for selection and optimization, e.g. maximum EYR and ESI with medium EIR (Brown and Ulgiati, 1997; Zhang et al., 2016). However, more and more recent results explored the potential risks of solely utilizing these classical indices as objective functions. For example, it was found that systems with close ESI may have significantly different economic viability and short-term sustainability (Lu et al., 2017), and the EIR of a high economic input agriculture system may not be high because the cost of non-renewable resources (Amiri et al., 2019). Similar problems were also explored by this study, e.g. EYR had a positive relationship with crop yield and a non-linear positive relationship with SEE (Figs. 3b and 4c), indicating that the high system return on the purchased resources in farmland of LP might accompanied with high soil erosion risk. Meanwhile, high EIR, companied by the overutilization of nitrogen fertilizers, could increase GWF, and finally lead to a decrease of ESI ((Fig. 4a, 4b, 4e). All these results confirmed the necessity of an integrated consideration of specific key ecological economic issues (such as grey water depletion and soil erosion problems on LP in this study) of the system under study with fundamental emergy indices for both evaluation and optimization strategy making.

Three optimization strategies can be used for different kinds of unsustainable farmland ecosystems (Fig. 5). (1) For counties with high GWFs (i.e., GWF >500 m^3/t), reducing the utilization of chemical fertilizers (i.e., nitrogen fertilizer) or adjusting the economic inputs, such as replacing chemical fertilizer with organic fertilizer (Tuo et al., 2017) or crop residue retention (Ranaivoson et al., 2017), might be beneficial to ecosystem sustainability. For example, we found that CY, GWF and EIR of the maize production in LanTian County and Hu County were 13530.23 kg/ha, 775.17 m^3/t and 68.50, and 14309.38 kg/ha, 839.83 m^3/t and 61.29, respectively, while those of their neighboring county, Huazhou County (which had similar annual precipitation), were 14519.04 kg/ha, 231.30 m^3/t and 60.41, respectively. This indicated that a modest reduction in chemical fertilizer utilization in high GWF counties will not necessarily lead to a reduction in food production but to a decrease in environmental pressure. (2) We found that all the counties with high SEEs had low EIRs, showing that the economic inputs to the agricultural system in these counties were relatively low. Therefore, it is necessary for such counties to increase their economic inputs or to change the management methods, such as to increase their investment in soil protection measures or to use some conservation agriculture techniques (e.g., no/reduced tillage) (Corbeels et al., 2020). (3) For counties with both high GWF and SEE, the structures of their economic inputs should be adjusted to reduce the environmental impacts, i.e., to decrease the inputs of chemical fertilizers and to increase the soil protection measures.

4.4. The application of crop switching can achieve sustainable yield in dryland farming

From the perspective of precipitation and environmental sustainability aspect, the counties in the LP were divided into 4 categories with different optimization targets and principles of crop switching simulation (Table 1). For example, for the relatively sustainable counties in prec <400 mm region, the optimization target was to improve the water productivity. For the relatively unsustainable counties in the prec <400 mm region, the optimization target was to reduce the environmental impacts, and the principle of crop switching accordingly was to reduce the GWF and SEE of the existing farmland (Table 1).

With the increase in harvest area involved in crop switching, the number of relatively unsustainable counties with high GWF or SEE (i.e., with GWF >500 m^3/t or SEE >1.5E+12 sej/ha) gradually decreased from 77 to 39 from scenario 1 to scenario 4 (Figs. 6 and S12). This

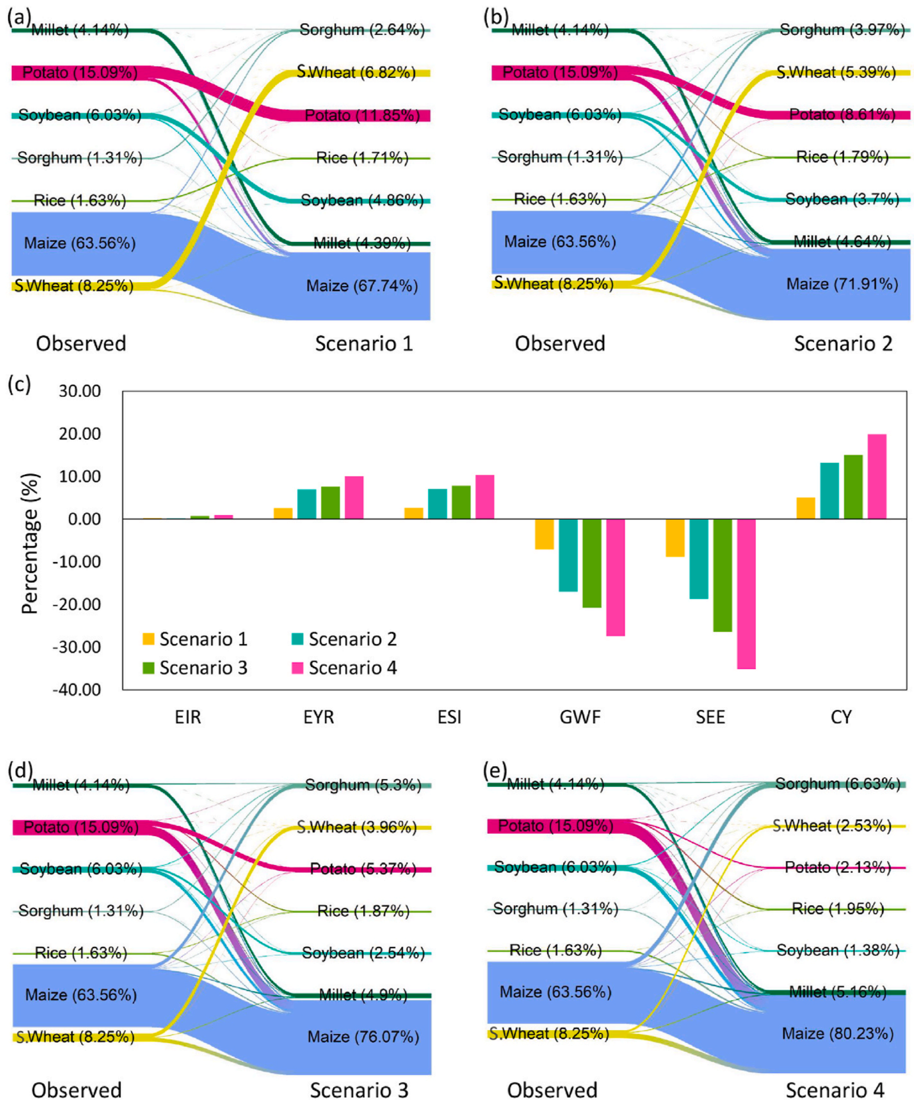

Fig. 7. The optimization progress of the four crop switching scenarios (a, b, d, e), and the difference of all indictors between the optimized results and observed data (c). In (a, b, d, e), the left line indicates the original harvest areas of crops, and the right lines indicate the optimized harvest areas of crops. EIR, EYR, ESI, GWF, SEE, and CY refer to emergy investment ratio, emergy yield ratio, emergy sustainability index, grey water footprint, soil erosion empower, and crop yield, respectively.

indicated that crop switching could contribute to the sustainable yield increase of farmland in LP. In studying the adaptation strategy of crops to climate change, Tessema et al. (2019) also showed that crop switching was beneficial to farmland sustainability. However, the function of crop switching is not unlimited because there were still some counties with high GWF or SEE (i.e., GWF >500 m^3/t or SEE >1.5E+12 sej/ha) in scenario 4. In addition, the harvest areas of maize and sorghum found increased after optimization (Fig. 7), which indicated that the two crops had a high potential to be expanded and planted in LP. From the optimization results, we found that the EYR, ESI and CY can be improved by 10.04%, 10.35% and 19.90%, respectively, and the GWF and SEE can be decreased by 27.41% and 35.14%, respectively, with all farmland being involved in crop switching (Scenario 4, Fig. 7c). These results further confirmed that the crop switching strategy has a high application potential in achieving a sustainable yield increase.

Sustainable food production has been recognized as the greatest challenge of the 21st century because of climate change and declining soil fertility in the dryland farming. Ghimire et al. (2018) reported that agricultural sustainability in semiarid drylands should include the following components: (1) optimizing resource use and conservation, (2) optimizing crop production and quality, (3) maintaining environmental quality, (4) meeting the economic goals of farmers and (5) strengthening social wellbeing. In this study, a new systematic analysis method that incorporated crop production with socioeconomic inputs and environmental impacts was developed. The integration of the new method and crop switching was verified as an efficient strategy for improving the crop yield and ecological economic viability of farmland, and for maintaining environmental quality by optimizing resource utilization and conservation.

5. Conclusions

Besides crop yield, which is the ultimate goal of crop switching studies, the integrated emergy system model and crop switching analysis method brought economic inputs and environment impacts of farmland into accounting, providing a much comprehensive view of the sustainability of farmland ecosystems. There were several important conclusions in this study: (1) The counties where the farmland ecosystem had a GWF >500 m^3/t or a SEE >1.5E+12 sej/ha can be defined as the relatively unsustainable counties in LP, which can be further optimized by adjusting the intensity and structure of the economic input to the farmland. (2) Maize and sorghum have high expansion potential in LP, and the technique of crop switching can be used as an effective strategy for achieving a sustainable increase in regional grain production. (3) The systematic analysis method developed this study has high application value for researching the sustainable intensification of grain production, especially for dryland areas with fragile ecological environments and prominent food demand-supply conflicts.

CRediT authorship contribution statement

Taotao Han: Conceptualization, Methodology, Software, Writing – original draft. **Hongfang Lu:** Conceptualization, Methodology, Writing – review & editing. **Yihe Lü:** Writing – review & editing. **Yanpeng Zhu:** Writing – review & editing. **Bojie Fu:** Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.135456.

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