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RESEARCH ARTICLE

TRADE-OFFS IN THE DESIGN OF SUSTAINABLE CROPPING SYSTEMS AT A REGIONAL LEVEL: A CASE STUDY ON THE NORTH CHINA PLAIN

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KEYWORDS

crop rotation, food security, multi-objective optimization, water use

HIGHLIGHTS

- Impacts of 30 cropping systems practiced on the North China Plain were evaluated.
- Trade-offs were assessed among productive, economic and environmental indicators.
- An evolutionary algorithm was used for multi-objective optimization.
- Conflict exists between productivity and profitability versus lower ground water decline.
- Six strategies were identified to jointly mitigate the trade-offs between objectives.

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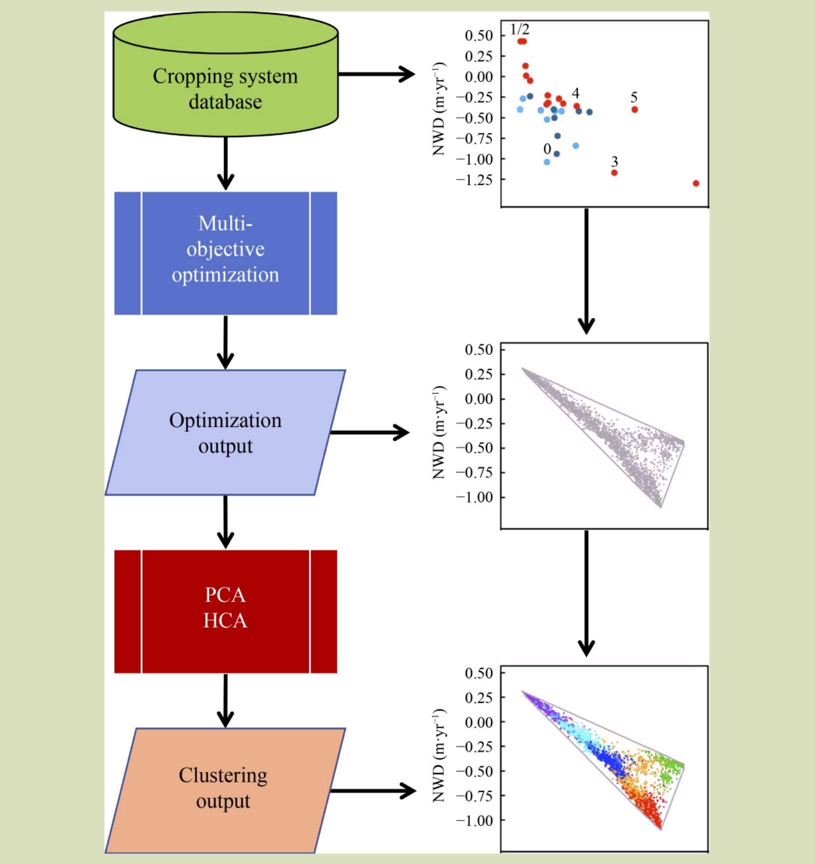
GRAPHICAL ABSTRACT



ABSTRACT

Since the Green Revolution cropping systems have been progressively homogenized and intensified with increasing rates of inputs such as fertilizers, pesticides and water. This has resulted in higher crop productivity but also a high environmental burden due to increased pollution and water depletion. To identify opportunities for increasing the productivity and reducing the environmental impact of cropping systems, it is crucial to assess the associated trade-offs. The paper presents a model-based analysis of how 30 different crop rotations practiced in the North China Plain could be combined at the regional level to overcome trade-offs between indicators of economic, food security, and environmental performance. The model uses evolutionary multi-objective optimization to maximize revenues, livestock products, dietary and vitamin C yield, and to minimize the decline of the groundwater table. The modeling revealed substantial trade-offs between objectives of maximizing productivity and profitability versus minimizing ground water decline, and between production of livestock products and vitamin C yield. Six strategies each defining a specific combination of cropping systems and contributing to different extents to the various objectives were identified. Implementation of these six strategies could be used to find opportunities to mitigate the trade-offs between objectives. It was concluded that a holistic analysis of the potential of a diversity cropping systems at a regional level is needed to find integrative solutions for challenges due to conflicting objectives for food production, economic viability and environmental protection.

1 INTRODUCTION

Cropping systems occupy a large proportion of the land used for agriculture. They have been intensified to feed a growing global population with a strong focus on dietary energy production with less attention given to the supply of nutrients and vitamins in the human diet[1,2]. Since the Green Revolution, crop yields have doubled but losses of nutrients and pesticides to the environment and the extraction of water have more than tripled[3]. Throughout South Asia, cereal-based cropping systems are characterized by high levels of inputs, such as fertilizers, pesticides and energy, and significant environmental impacts[4,5]. Many technologies have been proposed and investigated to increase resource use efficiency, such as reduced or zero tillage and precision agriculture to reduce water use for irrigation, and losses of nutrients from fertilizers and toxic substances from pesticides[6,7]. The integrative approach of conservation agriculture that combines reduced tillage, diversified crop rotations and increased soil cover by mulching has been broadly tested[8,9]. Resource-saving and pollution reducing measures for cropping systems have been evaluated primarily at the field level, while regional level studies to redesign cropping systems are scarce.

These trends in intensification of cereal-based cropping systems, and the resulting resource depletion and pollution[10] and increased attention for resource use efficiency to mitigate their negative environmental impacts[11,12] have also been observed on the North China Plain (NCP), which represents 23% of grain production in China[13]. Since the 1960s, policies to improve food security and self-sufficiency have led to enhanced cereal production and to dominance of the winter wheat-summer maize (WM) double cropping system on the NCP. This double cropping has resulted in a substantial increase in the use of groundwater for irrigation due to the large gap between annual precipitation (ca. 500 mm) and evapotranspiration (ca. 850 mm)[14]. Currently agriculture accounts for 62%–70% of water use on the NCP[15]. Consequently, groundwater storage has continues to decline[16] and most of the counties on the NCP (84%) are faced with water shortages[17]. Also, the pollution of water with heavy metals, organic material and in particular nitrate from agriculture have compromised the quality of shallow groundwater of the NCP[14]. Despite modest improvements in efficiency of crop production, the total volume of pollutants has steadily increased[18]. Considering the importance of the NCP for food security of China and as one of the regions experiencing crucial challenges in reconciling profitable and adequate food production with ecosystem and resource conservation, the NCP is suitable for regional-level case studies and analysis of the opportunities for sustainable intensification.

To address the challenges of reducing pollution and water use while stabilizing crop productivity, experiments have been conducted to test contrasting cropping systems that differ in crop combinations and management practices by Xu et al.[19] and Yang et al.[20]. Yang et al.[21] evaluated and compared 30 cropping systems for their potential to reverse groundwater depletion while achieving economic and food security co-benefits. These systems contribute to various objectives in three dimensions of agricultural sustainability, namely, economic profitability, food production and environmental impact, in different ways. Therefore, no single solution but rather combinations of multiple cropping systems are expected to be effective in addressing the range of concerns. Similarly, Liu et al.[22] have assessed the impacts of crop allocation on water use on the NCP using a spatially explicit, multi-objective optimization modeling approach. Here, we explore the potential impact of combining multiple cropping systems on a range of performance indicators representing the three agricultural sustainability dimensions at the level of the NCP.

Although national interests require a balance between food security and the conservation of resources and ecosystems, attempts to improve the performance of land-use systems are often confronted with trade-offs, a situation that has been identified for the conflicts between water security and water quality versus food security on the NCP[14]. At the field level, for the WM double cropping system this was illustrated in the crop modeling study of Ren et al.[23]. The trade-offs are related to choices in allocation of resources, including space and time, and occur when multiple activities, purposes and functions are pursued[24]. Trade-offs can be formulated as an allocation-problem when a finite resource cannot be used for another purpose, at another time or in another place, or as a function-problem signifying that the outcomes for a certain function cannot be further improved without sacrificing the performance in terms of one or more other functions. In dealing with these decision-making problems positives and negatives that must be weighed against each other in the selection between competing options and outcomes[25]. Making a prioritization and deciding on choices is a value laden process[26].

Trade-off analysis tools are designed to enable insight into the trade-offs that are involved in land-use decisions and to inform stakeholder discussions and decision-making and planning processes[27]. Most methodologies used to explore trade-offs are model-based due to the inherent complexity of the analysis[28–31]. Interactions among multiple indicators are assessed in an integrated way to demonstrate their interactions, and to establish to what extent the performance of a selected indicator can be improved in concert with, or without sacrificing, other indicators. Also, the land-use systems that are analyzed comprise a heterogeneous set of biophysical and socioeconomic components that operate at multiple hierarchical levels and spatiotemporal scales.

In this paper, we address the trade-off between food security and economic revenues versus environmental impact of cropping systems at the regional level on the NCP. We translate the various interests into relevant indicators and apply a multi-objective optimization approach to explore relationships among indicators, which may be synergistic, conflicting (trade-offs) or indifferent. Instead of focusing on single cropping systems, practices or technologies, we assess the regional-level impacts of complete crop rotations, in combination with animal production from crop residues. Hence, the objective of this study was to explore trade-offs and synergies among production, nutritional and resource efficiency objectives and determine how insight into these trade-offs and synergies can inform decision-making on land-use and cropping system design at the regional level for a case study on the NCP.

2 METHODS

2.1 Methodological framework

The methodological framework is presented in Fig. 1. Cropping systems data (Section 2.2) quantified the performance of 30 crop rotations for five indicators (Section 2.3). These data were used in multi-objective optimization powered by an evolutionary algorithm (Section 2.4) to determine trade-offs and synergies among the five objectives that were derived from the cropping system indicators with a direction of desired change added. This resulted in a set of alternative cropping systems configurations (solutions) for the case study region. The evolutionary algorithm of differential evolution was used for multi-objective optimization (Section 2.5) and used Pareto optimality and crowding as selection criteria for evolutionary improvement of the set of solutions (Section 2.6). Subsequently, principal component analysis and hierarchical cluster analysis were used to find consistent patterns of cropping system combinations within the set of solutions, as described in Section 2.7.

2.2 Cropping system data

The database of cropping systems which were tested in research on the NCP during the period 1990–2020 in field experiments or in validated crop models as compiled by Yang et al.[21] was used in this study. The database contained 30

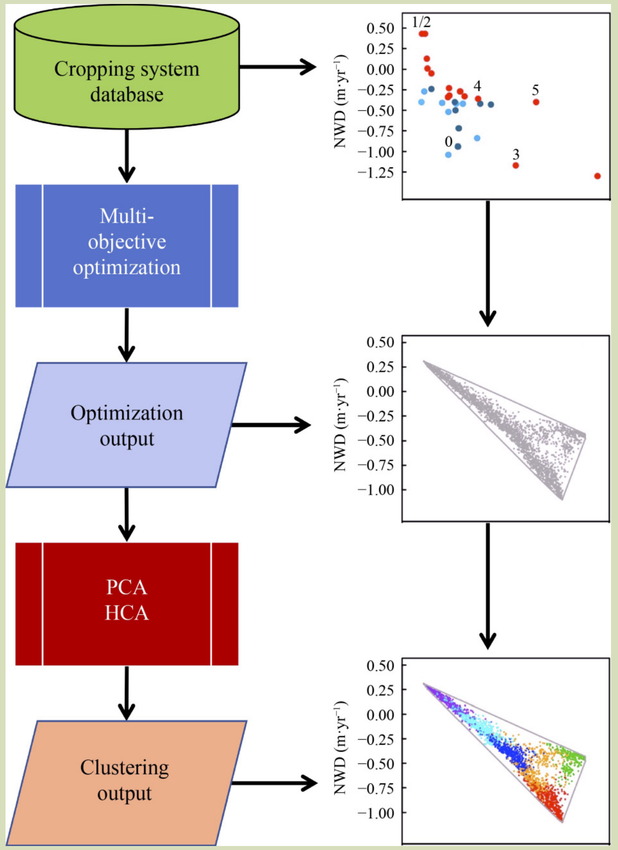


Fig. 1 Methodological framework of the research. PCA, principal component analysis; HCA, hierarchical cluster analysis.

cropping systems (see Table S1) including WM with irrigation and rainfed treatments, six monocultures with both irrigation and rainfed treatments, two perennial crops (alfalfa and switchgrass with irrigation), 10 double cropping systems with two harvests per year, six rotations comprising WM double cropping in one of the years, alternating with a year with a single harvest (i.e., with three harvests in 2 years), and five multi-year cropping systems with rotation cycles longer than 2 years.

2.3 Indicators

The impact of cropping systems on water resources was reflected in the net groundwater decline (NWD; $\text{m}\cdot\text{yr}^{-1}$)[20,21], see Eq. (1). Negative values of NWD indicate groundwater depletion (decreased storage in the aquifer) and positive values indicate increased aquifer storage:

$$\mathrm{NWD} = \mathrm{D} - \mathrm{I} \tag{1}$$

where, D is deep percolation ($\text{m}\cdot\text{yr}^{-1}$) and I is irrigation ($\text{m}\cdot\text{yr}^{-1}$).

The economic outcome was quantified as the gross revenues from cropping per year averaged over the duration of the rotation ($\mathrm{R_Y}$; $\text{CNY}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$):

$$\mathrm{R_Y} = \frac{\sum_{i=1}^{n} \mathrm{Y}_i \mathrm{P}_i}{\mathrm{D}} \tag{2}$$

where, Y_i is the yield of the product of crop i ($\text{Mg}\cdot\text{ha}^{-1}$), P_i is the price of the crop product ($\text{CNY}\cdot\text{Mg}^{-1}$), n is the number of crops cultivated in the cropping system and D is the duration of the rotation (years).

The food production dimension was captured in indicators of nutritional systems yield (persons $\text{ha}^{-1}\cdot\text{yr}^{-1}$), which reflects the number of people that can be supported from the products of a cropping system in terms of a nutrient or food group (Eq. (3); adapted from DeFries et al.[2]; see also Timler et al.[32]) This indicator was calculated for livestock products, dietary energy and vitamin C ($\mathrm{NSY_{LP}}$, $\mathrm{NSY_{DE}}$ and $\mathrm{NSY_{VC}}$, respectively).

$$\mathrm{NSY}_r = \frac{\left(\sum_{i=1}^{n} \mathrm{F}_i \mathrm{P}_{r,i} + \sum_{j=1}^{m} \mathrm{F}_j \mathrm{P}_{r,j}\right)}{\mathrm{DRI}_r} \tag{3}$$

where, r is the nutrient or food group (e.g., dietary energy, vitamin C and livestock products), F_i is the fresh weight produced ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) of crop product i, $\mathrm{P}_{r,i}$ is the content of nutrient r in crop product i ($\text{g}\cdot\text{kg}^{-1}$), F_j is the fresh weight ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) of animal product j, $\mathrm{P}_{r,j}$ is the content of nutrient r in animal product j ($\text{g}\cdot\text{kg}^{-1}$), DRI_r is the dietary reference intake for nutrient r for a person per year (g per person per year), and n and m are the number of crop and animal products, respectively.

The dietary energy and vitamin C demand per person were expressed as dietary reference intakes as quantified by the recommended dietary allowance for a male adult of 30-year-old as a reference[33]. The dietary energy and vitamin C content of foods was extracted from the USDA food database.

Animal production was expressed as the number of consumer units that can be fed with livestock products per unit of area (km^2) and was derived from the amount of fodders produced (alfalfa, ryegrass and sorghum) converted to pork and dairy products, in a ratio equivalent to Chinese average consumption of pork (95 g per person per day) and dairy (33 g per person per day)[34]. The conversion efficiencies were derived from Shepon et al.[35] and Alexander et al.[36]. We have assumed that sweet potatoes serve as human food for 30% of the production, and thus contributes to dietary energy supply, while the remainder is fed to animals.

2.4 Multi-objective optimization

Pareto-based evolutionary multi-objective optimization was used to determine which combinations of cropping systems could best satisfy the requirements of economic profitability, food production and water use efficiency. The objectives were to: (1) maximize economic revenues (R_Y), (2) minimize decline of the water table (NWD), (3) maximize the production of livestock products (NSY_{LP}), (4) maximize the supply of dietary energy from the system (NSY_{DE}), and (5) maximize the supply of vitamin C from the system (NSY_{VC}).

A multi-objective optimization problem that can generally be represented by the following equations:

$$\mathrm{Max}\,U(x) = (U_1(x), U_2(x), \ldots, U_k(x))^T \tag{4}$$

$$x = (x_1, x_2, \ldots, x_n)^T \tag{5}$$

subject to *i* constraints:

$$g_i(x) \leqslant h_i \tag{6}$$

where, $U_1(x), \ldots, U_k(x)$ are the objective functions that are simultaneously maximized or minimized, and $x_1, \ldots, x_n$ are the decision variables that can take on a prescribed array of values, $\mathbf{x} \in S$, where S is the solution or parameter space. These define cropping system areas, residue allocation and animal numbers that are adjusted during the optimization. Constraints in Eq. (6) can arise from the problem formulation, for example by limitations on model results related to a specific configuration of decision variables. In this case, constraints pertain to the total cropping area that cannot be exceeded and the supply of energy in feed that should match the requirements for animal production. An overview of decision variables, constraints and objectives is provided in Table S2.

2.5 Evolutionary algorithm: differential evolution

The optimization problem was addressed with a multi-objective Pareto-based differential evolution algorithm. Differential evolution[37] belongs to the family of evolutionary algorithms, consisting of adaptive search techniques based on the principles of natural evolution. These algorithms belong to a class of heuristic algorithms. The procedures are called heuristic because there is no formal mathematical guarantee of convergence to the optimal solution, as is the case for so-called mathematical programming methods, such as linear programming.

Genetic operators for reproduction, selection, mutation and crossover (the latter only in so-called genetic algorithms) are applied to a set of solutions or genotypes, consisting of alleles. A genotype is a multi-dimensional vector $p = (p_1,\ldots,p_z)^T$ of z alleles. The genotypes define the land-use on the NCP landscape. The alleles represent the decision variables and thus define the areas of the cropping systems in the landscape, residue allocation and animal numbers. Each allele p_i is initialized as $p_{i,0}$ by assigning a random number within the range allowed for individual decision variables. A new generation $t + 1$ is created by applying mutation and selection operators on each of the individuals in the population P of the current generation *t*. The first step of the reproduction process is generation of a trial population P' that contains a counterpart for each individual in the parent population P, produced by parameterized uniform crossover of a parent vector and a mutation vector (Eq. (7)). The mutation vector is derived from three mutually different competitors c_1, c_2 and c_3 that are randomly selected from the population P in the current generation *t*. The allele values of the individual in the trial population are taken from the mutation vector with probability C_R and with probability $(1–C_R)$ copied from the parent:

$$p'_{i,t+1} = \begin{cases} c_{3,1} + F \cdot (c_{1,i} - c_{2,i}), r_i < C_R \\ p_{i,t}, \text{otherwise} \end{cases} \tag{7}$$

where, r_i is a uniformly distributed random variable. The parameter $F \in [0,2]$ is a parameter that controls the amplification of differential variations. After a mutation, the value of $p'_{i,t+1}$ can extend outside of the allowed range of the search space. For allele values that violate the boundary constraints of the back-folding repair rule is applied[38]. A trial genotype p'_{t+1} replaces p_t if it outperforms the parent genotype. Here, better performance is interpreted as a better Pareto ranking or a location in a less crowded area of the search space than the parent genotype (Section 2.6). Here we used a population of 2500 genotypes and performed 1000 iterations of optimization with differential evolution algorithm parameters crossover probability C_R of 0.85 and mutation amplitude F of 0.15. Detailed descriptions of implementation of this algorithm are given by Groot et al.[38,39].

2.6 Selection criteria: Pareto optimality and crowding

The first criterion for the performance of a solution is its

Pareto rank as proposed by Goldberg[40]. Individuals in the population are Pareto-optimal when they do not perform worse than any other individual for all the objectives, that is when they perform equal to or better than any other individual in at least one objective. In such case, there is no objective basis to discard the individual. These individuals are called non-dominated and receive rank 1. This set of solutions is called the trade-off frontier. The next step in Pareto-ranking the entire population of solutions is to remove the individuals of rank 1 from the population and identify a new set of non-dominated individuals, which is assigned rank 2. This process is continued until all individuals in the population are assigned a Pareto rank. When the prior information of the performance of the original farming system is used, the ranking mechanism of Goldberg[40] may be slightly adjusted to improve the exploration of that part of the solution space where solutions are found that perform better than the original farm configuration.

If two solutions have the same rank, a second selection criterion, the crowding distance, is considered. The metric Θ represents the within-rank solution density and is calculated from the normalized distance from solution i to the nearest solution in the search space[41] as:

$$\Theta_i = \sum_{j=1}^{k} \frac{\left|d_{i,j} - d_j\right|}{\left|B_j\right|} \tag{8}$$

where, B_j is the range of objective j, which is calculated as the difference between the minimum and maximum values of objective j. Variable $d_{i,j}$ denotes the Euclidian distance between solution i and the nearest neighbor solution within the Pareto front of a given rank and the parameter d_j is the average of these distances. An individual is replaced by a trial solution of the same rank if the latter is in a less densely populated part of the solution space.

2.7 Statistical analysis

The multi-objective optimization generated 2500 solutions that represented alternative land-use options with different cropping system allocations for the cultivated area in the landscape. To identify coherent strategies and correlations between decision variables and objectives, a principal component analysis (PCA) and hierarchical cluster analysis (HCA) were conducted. HCA was performed on the principal components identified by PCA using function *dudi-pca* of the R package “ade4”. The function *hclus* was used to generate a dendrogram from which the number of clusters was derived and function *cutree* was then applied to assign the solutions to the clusters.

3 RESULTS

The performances of the individual cropping systems varied markedly (Fig. 2). The largest amount of vitamin C was produced by the spinach-spring maize rotation, which reached a nutritional system yield sufficient to nourish 646 persons $\mathrm{ha^{-1}\cdot yr^{-1}}$. The ryegrass-sorghum cropping system reached the highest production of livestock products and highest economic revenues but produced no vitamin C and a small quantity of dietary energy, while leading to a substantial decline in groundwater. Only four crop rotations would be able to avoid groundwater depletion, of which rainfed spring peanut and rainfed spring soybean were the most effective with 0.43 m of positive effect. Fourteen of the 30 crop rotations were Pareto-optimal. The most dominant cropping system on the NCP is irrigated WM with an acceptable profitability of 8021 $\mathrm{CNY\cdot ha^{-1}\cdot yr^{-1}}$ and dietary energy production for 53.7 persons $\mathrm{ha^{-1}\cdot yr^{-1}}$, while it produces no vitamin C and causes a considerable NWD decline of 1.03 $\mathrm{m\cdot yr^{-1}}$ (Fig. 2, indicated by 0). The WM system received Pareto-rank 3 within the set of 30 cropping systems and can therefore be considered as suboptimal.

Figure 3 presents the results of multi-objective optimization with 30 cropping systems. There were synergetic relations between economic revenues and the production of dietary energy (Fig. 3(d)) and livestock products (Fig. 3(b)). However, an increase in these indicators was associated with increased groundwater decline (Fig. 3(a,c,e)), indicating substantial trade-offs. Also, vitamin C production would be reduced with an increase of livestock production (Fig. 3(i)), and when revenues would increase beyond 18,000 $\mathrm{CNY\cdot ha^{-1}\cdot yr^{-1}}$ (Fig. 3(g)) and when dietary energy production would be enhanced to a quantity sufficient to feed more than 55 persons $\mathrm{ha^{-1}\cdot yr^{-1}}$ (Fig. 3(j)).

A cluster analysis based on the indicator performance and areas of crop rotations in the solution set from the optimization resulted in six clusters each containing between 11% and 20% of the solutions (Fig. 3 and Fig. 4). The resulting clusters of the Pareto-optimal solutions were interpreted as cropping strategies. These were dominated by five cropping systems, that were allocated different proportions of the cropping area in the clusters (Fig. 4). Clusters 1 and 2 achieved the highest economic revenues by cultivating a large area of either the sweet potato-cotton-sweet potato-WM rotation or the ryegrass-sorghum-WM rotation. Cluster 3 had the highest

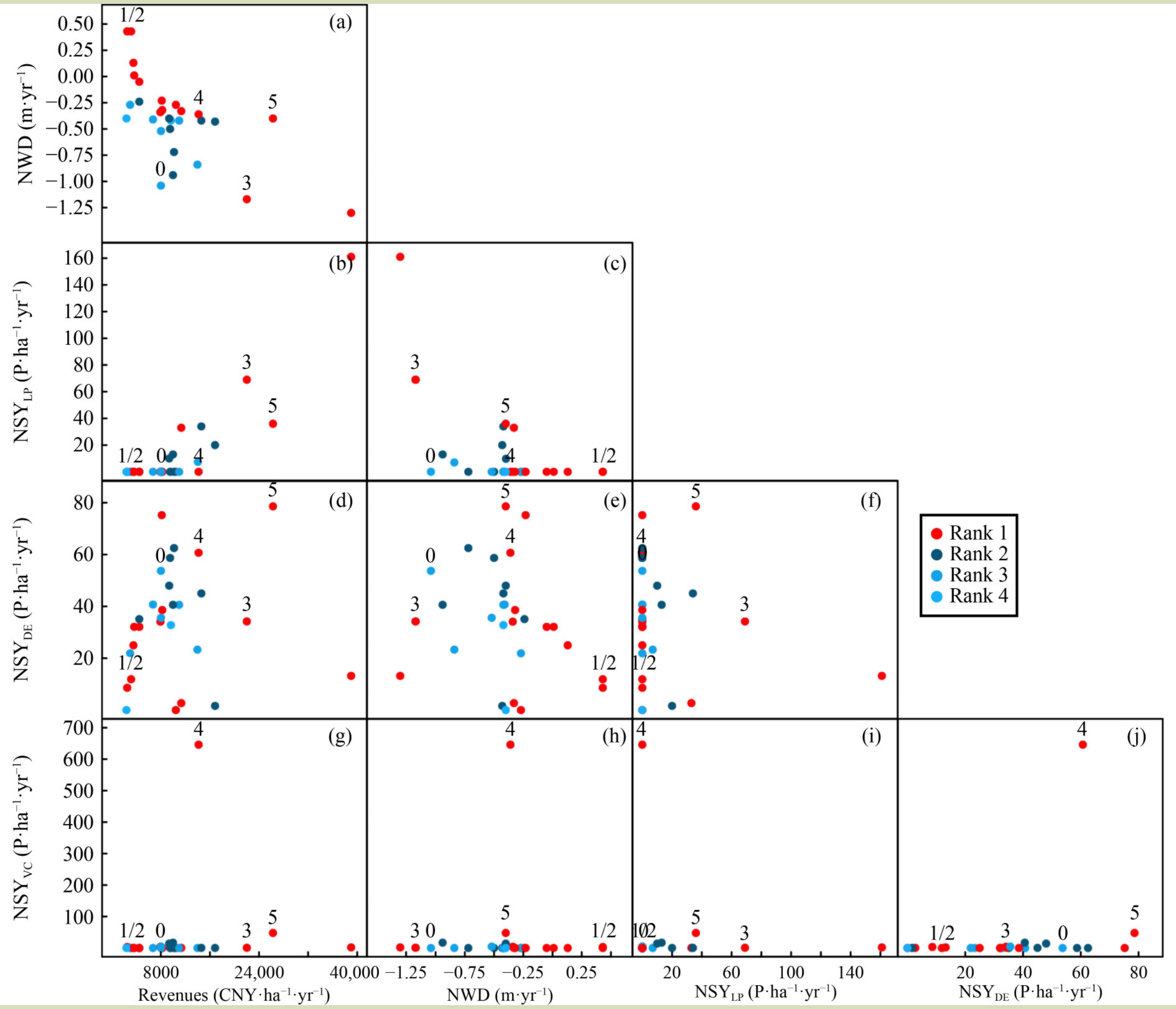


Fig. 2 Performance of cropping systems in terms of the selected model indicators of economic revenues, decline in water table (NWD) (a), nutritional systems yield of livestock products (NSY_{LP}) (b, c), dietary energy (NSY_{DE}) (d–f), and vitamin C (NSY_{VC}) (g–j). The dominant cropping system of winter wheat-summer maize is labeled as 0 and the five most frequently selected cropping systems in the multi-objective optimization as 1 to 5 (see Table 1). Cropping systems 1 and 2 overlap for most indicators and are indicated with '1/2'. P, persons.

vitamin C production which was largely derived from the spinach-spring maize cropping system. By combining three cropping systems, the lowest groundwater decline was achieved by solutions of clusters 5 and 6.

Five scenarios were created based on the median cropping areas within the clusters. These scenarios (Table 1) comprised two economic scenarios derived from clusters 1 and 2, respectively, a nutrition scenario informed by clusters 3 and 4 and an environmental scenario resulting from a combination of clusters 5 and 6. The last scenario as created as a compromise between the various objectives (Table 1). The compromise scenario contained the five dominant crop rotations and combined intermediate levels of economic revenue, dietary energy production and ground water decline with relatively low levels of vitamin C and livestock production. The percentages of area occupied by crop rotations were similar, only the proportion of the rainfed spring soybean cropping system (8%) was substantially lower than the other crops (19%–27%; Table 1). The compromise scenario would still maintain a considerable amount of groundwater decline. If the aim is to avoid groundwater depletion, then the maximum attainable revenues would be 11,587 CNY·ha^{-1}·yr^{-1} and nutritional systems yield of dietary energy and vitamin C of 31 and 39 persons ha^{-1}·yr^{-1} and 19 persons ha^{-1}·yr^{-1} could be fed with livestock products. In that case the percentage of rainfed

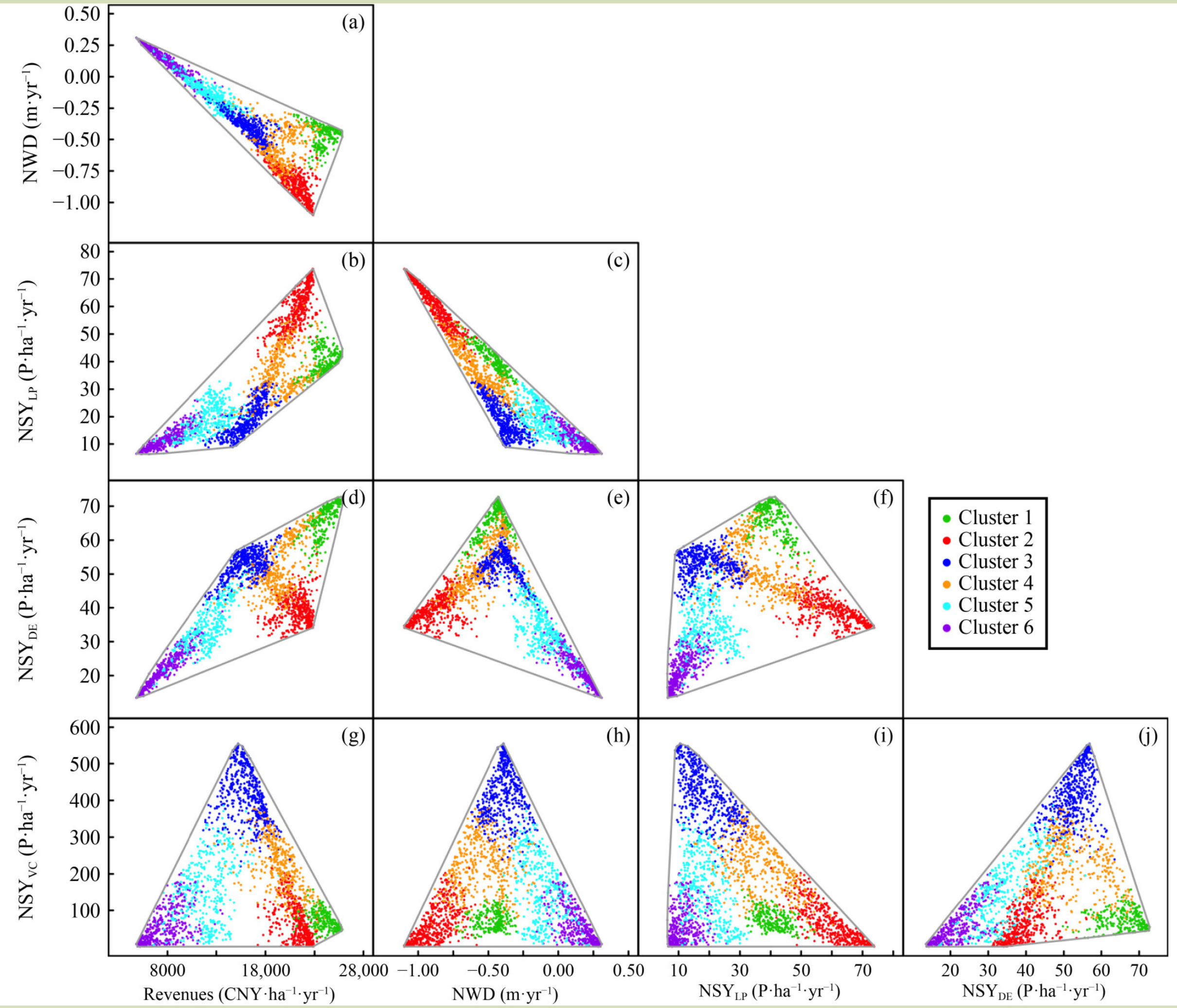


Fig. 3 Relationships between indicators in the multi-objective optimization: economic revenues, decline in water table (NWD) (a), nutritional systems yield of livestock products (NSY_{LP}) (b, c), dietary energy (NSY_{DE}) (d–f), and vitamin C (NSY_{VC}) (g–j). The result set contained 2500 configurations; each dot represents a different configuration of cropping system areas. The set of options is surrounded by a “hull” (gray line). Solutions were clustered into six clusters based on objectives and cropping system areas. P, persons.

spring peanut and soybean would be large (41% and 15%, respectively) and the more water demanding cropping system of sweet potato-cotton-sweet potato-WM would be reduced to 20%.

4 DISCUSSION

The set of available cropping systems showed a large variation in the five indicators that were selected to represent the economic, food security and environmental performance. The five most promising cropping systems that could contribute to reconciling the various objectives were in the Pareto-optimal subset (Fig. 1). In contrast, the most dominant cropping system on the NCP (irrigated WM) was characterized by high dietary energy production, but it produced no vitamin C and caused a considerable NWD decline. Therefore, it received Pareto-rank 3 and could be considered as suboptimal. The importance of the WM system is probably attributable to its contribution to staple food (cereal) production and the concomitant dietary energy supply thereby supporting food security. The economic revenues of 8021 CNY·ha^{-1}·yr^{-1} of WM were relatively low compared to other cropping systems, ranking twentieth among 30 cropping systems, but risks are also limited due to the availability of inputs (fertilizers, pesticides and water), and cultivation is standardized and highly mechanized alleviating farmers from more complex operational management and strategic decision-making.

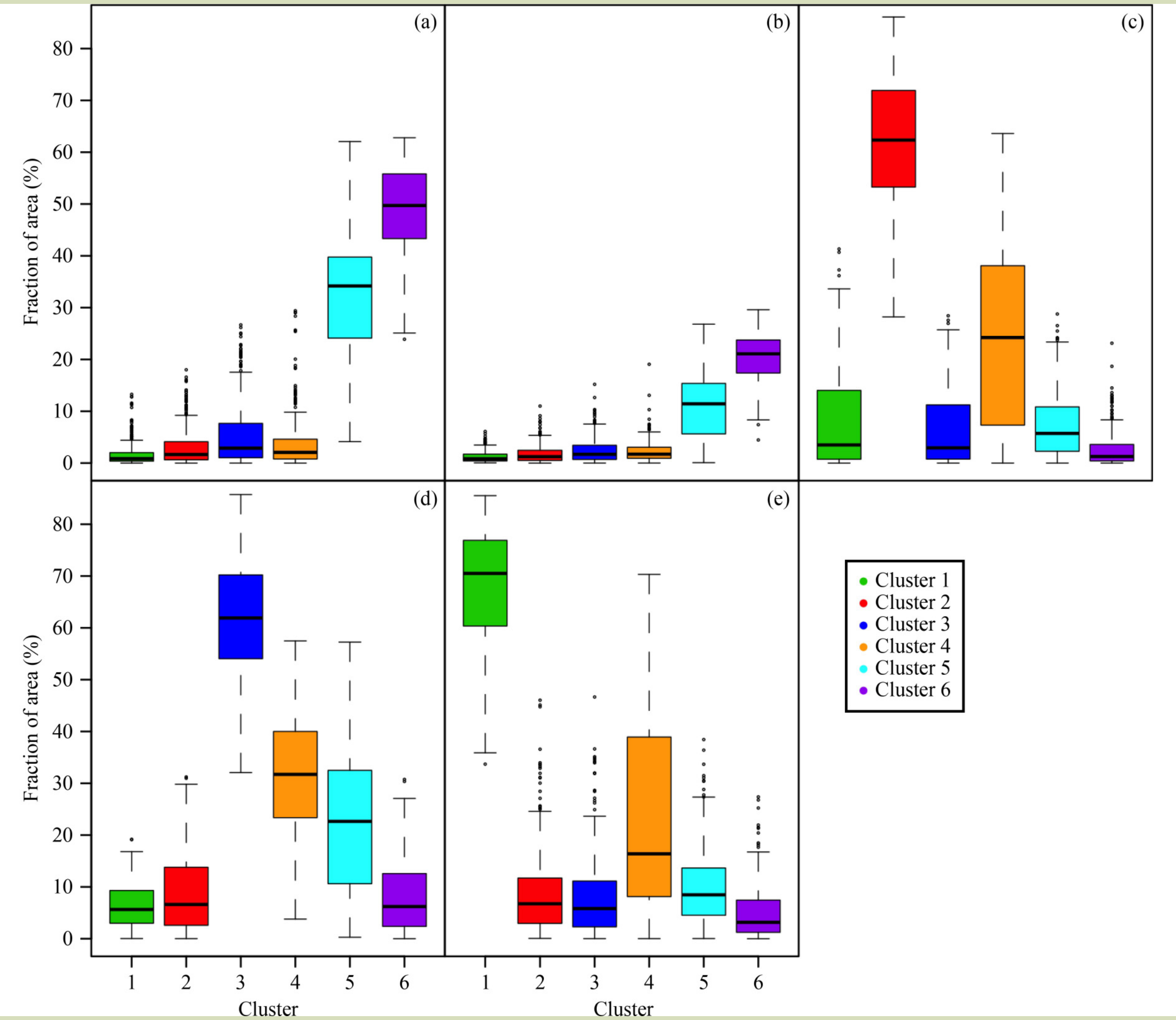


Fig. 4 Proportion of area occupied by five different cropping systems for six clusters in the solution set of the multi-objective optimization. Cropping systems: (a) rainfed spring peanut, (b) rainfed spring soybean, (c) ryegrass-sorghum-WM, (d) Spinach-spring maize, (e) sweet potato-cotton-sweet potato-WM. WM, winter wheat–summer maize.

By combining multiple cropping systems, synergies between economic revenues and the production of dietary energy and livestock products could be exploited, but this was associated with increased groundwater decline signifying a substantial trade-off (Fig. 3). Compared to the dominant irrigated WM cropping system, the compromise scenario (Table 1) would double economic revenues while reducing NWD decline and additionally providing considerable quantities of vitamin C and livestock products. Implementation of the more complex scenarios involving multiple cropping systems would require either diversification at farm level or regional coordination of cultivation of the various crops. At farm level this could lead to more diversified crop rotations that could be beneficial for soil and crop health. These benefits could be strengthened with further diversification by including root and tuber crops and vegetables. These crop types were underrepresented in the set of 30 tested cropping systems that were used in this study.

Our analysis used input-output coefficients of cropping systems as fixed parameters. This assumed homogenous management and did not consider biophysical variations throughout the case study region. More detailed analyses using a more granular approach toward crop cultivation practices and differences among farmers and including a spatial representation of the diversity soil conditions and water availability throughout the NCP would be warranted[42]. To tackle the trade-offs that were identified, innovative approaches to cropping would be needed, combining crop diversification,

Table 1 Proportions of cropping systems and performance indicators for five development scenarios focusing on economy, environment, nutrition or constituting a compromise

Item	Scenario				
	Compromise	Environment	Economy-1	Economy-2	Nutrition
Cropping system (% of area)					
Rainfed spring peanut	19	53	0	0	0
Rainfed spring soybean	8	17.5	0	0	0
Ryegrass-sorghum-WM	23	6	6.5	87	20
Spinach-spring maize	23	17.5	6.5	6.5	65
SP-cotton-SP-WM	27	6	87	6.5	15
Indicator performance					
Profit (CNY·ha^{-1}·yr^{-1})	16290	7510	25324	21942	17600
GWT decline (m·yr^{-1})	−0.344	0.146	−0.448	−1.067	−0.528
NSY dietary energy (persons ha^{-1}·yr^{-1})	46	25	75	39	58
NSY vitamin C (persons ha^{-1}·yr^{-1})	162	117	84	46	427
NSY livestock products (persons ha^{-1}·yr^{-1})	26	6	36	63	19

Note: SP, sweet potato; WM, winter wheat-summer maize; GWT, ground water table; and NSY, nutritional system yield.

genetic crop improvement, and more resource-efficient soil cultivation and crop management[43,44]. In addition to the need to improve water use efficiency[12,21], the cropping systems on the NCP require reductions in inputs of nutrients and pesticides and in emissions of greenhouse gasses[45,46].

The results of the multi-objective optimization and the preferred cropping systems and resulting scenarios are strongly dependent on the indicators that are included in the analysis. The narrow focus on productivity in the last decades led to the development of apparently efficient systems that contributed to food security and the supply of cereals. This study demonstrated the importance of employing a broader set of evaluation criteria, acknowledged of the existence of trade-offs and provided a methodology for integrated analysis. Considering the relevance of a one-health perspective aiming to strengthen both human health and environmental health[47,48], the indicator set could be further expanded. Important candidates are nutrition indicators related to dietary diversity and the supply of micronutrients and vitamins and environmental indicators for pollution, soil and agroecosystem integrity, pest and disease suppression and biodiversity[49,50]. The adoption of more holistic assessments is even more urgent given the expected acceleration of reductions in human and environmental health linked to the current socioeconomic developments of increasing incomes and urbanization[47] and biophysical trends of climate change and biodiversity decline[51].

The multi-objective optimization approach presented here optimizes several indicators simultaneously which allows a systematic exploration of innovation options to meet productive, economic, and environmental objectives. Rather than identifying scenarios or applying single, weighted or constrained optimization[30,52,53], we explore whole spaces of possible options available to land managers and policymakers[32]. Similar approaches have for instance been used to address the water-food-energy nexus using genetic algorithms[54] or Monte-Carlo simulation[22]. An important extension could be the explicit incorporation of uncertainty in the optimization, which could be caused by variability in system conditions (e.g., weather and prices) and the model formulation and data. The effects of uncertainty in model inputs on the optimization outcomes could be evaluated with algorithms of fuzzy programming[55] or multi-objective optimization under uncertainty[56,57].

The methodology presented in this paper should be considered as a component in a toolkit to be used for trade-off analysis. Various tools and methods exist for this purpose and can be used in concert, such as systems analysis and simulation, scenario building, cost-benefit analysis, and risk assessment[58]. These quantitative tools should be embedded in a participatory process involving relevant actors to address the trade-offs, because decision-making when facing trade-offs is unavoidably value laden[26]. It is therefore crucial to determine which and whose values contribute to the design and application of tools and in the use of deliberative processes[26,59]. The methodology and its results are particularly useful for policymakers and planners and other actors that are involved in governance at different levels (village, township, county, province and national).

Contrasting opportunities exist to address and alleviate trade-offs. If the scope for technological development for instance for improving the efficiency of cropping systems is limited or absent, then decisions should be made using the values of the involved stakeholders. This can be supported by multi-criteria decision-making approaches that weigh priorities, for example, based on private (farmer) and public (societal) interests[60]; this results in selecting the best compromise solution for the problem. Alternatively, if options for mitigation of losses and degradation and improvement of production and economic returns are present for the existing crops or cropping systems or by introducing new practices and technologies then these can be used to move the trade-off frontier in the desired direction toward synergistic improvements[61]; in this case it will be difficult to completely overcome the trade-off. Alternatively, when the trade-off is substantial, as in our case study between productivity and NWD decline, the problem could be transformed and alternative ways to fulfill objectives of the stakeholders can be considered, leading to integrative solutions. An integrated solution would lead to a better outcome for all actors than a compromise, but it takes more analysis and understanding of the agroecosystem and its management, a greater understanding of the needs of all stakeholders, and more creativity[62].

Most research on cropping systems and associated trade-offs on the NCP have focused on field-level analysis[63], individual inputs[64] or a narrow range of problems[45]. We see our approach as a starting point for more holistic analysis. In future research, more detailed reconfiguration of cropping systems in time and space, and of crop management is needed to improve performance of cropping systems. Also, technology development, exploiting ecological processes and ecosystem services and reconnecting crop and livestock production would be beneficial for contribution to support productive and environmental performance of cropping systems on the NCP. Our study provides a spatially implicit overview of opportunities with cropping systems that were tested for the NCP. Subsequent studies could focus on smaller subregions, such as selected counties on the NCP, or apply a more stratified analysis that incorporates the variability in biophysical and socioeconomic conditions found on the NCP. These contextual variations will affect crop responses and farmer preferences, strategies and decision-making.

5 CONCLUSIONS

Substantial trade-offs were identified between agricultural productivity and profitability versus ground water depletion. These trade-offs will be hard to overcome and will require considerable rearrangement of cropping systems on the NCP region, tuning of inputs and crop management and improvement of crop cultivars. The results demonstrate that moving from the dominating irrigated WM cropping system that currently dominates in NCP farms to more diversified systems would be promising but involves a combination of multiple strategies and cropping system choices and therefore requires spatiotemporal planning and coordination. For practical implementation, various objectives should be considered and weighed, then a compromise combination of cropping systems should be selected. Also, further options for diversification of the crop portfolio and for increasing the efficiency of cropping activities will be required. The methodological framework presented here proved useful for exploration of promising avenues for future development of cropping systems at a regional level, and to identify important conflicts and synergies that could occur. The framework is flexible and allows rapid expansion with new indicators, for example, related to environmental impact and nutrition-sensitive agriculture. Compared to other studies, the present study integrated multiple cropping systems and concerns and allowed evaluation of links with animal production. The trade-offs were visualized and made explicit, allowing analysis of problems from multiple perspectives and offering a diverse set of solutions. Dealing with the trade-offs will require intense discussion between stakeholders, creativity and innovation. Strong stakeholder interaction and policy support would be beneficial to identify integrative solutions that help to overcome stringent trade-offs.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2021434 contains supplementary materials (Tables S1–S2).

Compliance with ethics guidelines

Jeroen C. J. Groot and Xiaolin Yang declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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