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An optimal model of dry land multiple-cropping circular economy systems*

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Abstract. In the dry land agricultural systems, single-, double- and triple-cropped lands play different roles on ecological function, economic function and social function. In Sichuan province of China, the land area for various cropping patterns for three land types is in large proportion of Sichuan's cultivated land. It is extraordinarily important to obtain an optimal crop planting scheme based on the character of Sichuan province. In this kind of situation, this paper presents how multi-objective programming can be efficiently used for modeling and solving crop planning problems for optimal production of several seasonal crops in a planning year based on the scientific principle of circular economy and the character of Sichuan province dry land agriculture. The crop planning problem in agriculture is usually formulated as a single objective linear programming model. The objective is either the maximization of net revenue from cultivated land or the minimization of cost of cultivation. According to the national policies that ensure the stable growth of grain yield, this paper considers grain yield as an objective, use ε - constraint method and converts the multi-objective programming to a linear programming. The paper takes the Sichuan province of China into account as an illustrative case example and obtain some significative results by using RCGA.

Keywords: crop planning, multiple-cropping, optimal model, circular economy systems

1 Introduction

The circular economy is, essentially, an ecological economy that follows the principles of reducing resource use, reusing, and recycling, with the objectives of reducing the resources that enter the production process, effective multiple use of the same resources in various ways, and reusing waste from one facility as a resource for other facilities[7]. Agriculture which is closely related with the nature has the characteristic of resources recycling. Many researches in agricultural economics or farm management are about crop yield which is the most important problem in agriculture[1, 17].

Some papers research the environment and management factors influencing the yield, such as climate, tillage methods, residue management, row spacing, water irrigation, fertilizer, cropping patterns[10, 14, 21]. In these papers, crop yield is considered as a result of factors mentioned above. [6] examines the ecological basis for this high long-term productivity in a historical context, with a focus on the role of nutrient limitation. [20] builds a model developed to determine optimal irrigation strategies for a single season. [4, 16] solve the optimum management of the irrigation problem by applying genetic algorithm in agriculture. [3] focuses on the efficient flow of materials within an agroecosystem from cropping to livestock-raising and establish a functional model of the relationship between motive power and resistance with efficiency measured in terms of material flow within the system. Being different from papers focusing on environment and management factors influencing the yield, some papers focus on cropping decisions about land use and choosing the crops to be grown. Cropping decisions in farm and regional level mainly involve determining the crops to be grown

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and the area to be used for each kind of crop. Many papers have been written on this subject[9]. [15, 22] suggest the methods of multi-objective programming for land use in regional level planning. [2, 8] present how fuzzy goal programming can be efficiently used for modeling and solving land-use planning problems in agricultural systems for optimal production. [11] builds a model including multiple crops, market and nonmarket crop uses, and seasonality in production, consumption, and labor supply. Based on the above review, [18] considers a nation-wide crop-planning problem, formulates the problem as a goal program and discusses the importance of three different goals for a case problem. [19] uses a multi-criteria methodology aiming at researching the objectives actually followed by a farmer or by a homogeneous group of farmers to analyze and predict the behavior of family farms. Thus, this paper studies cropping decisions based on the character of Sichuan province and present an optimal model of dry land multiple-cropping circular economy system to quantitatively analyze how to determine the crop planning to increase the crop yields and farmers's economic income .

This paper is organized as follows: section 2 presents the problem and then builds an optimal model for dry land multiple-cropping circular economy system. Section 3 gives an illustrative case example based on the conditions of Sichuan province by using real-coded GA. At last, section 4 comes to the conclusion.

2 Modeling

Under the direction of principle of circular economy, firstly, section 2.1 describes the problem. Then section 2.2 builds the optimal model of dry land multiple-cropping circular economy system.

2.1 Problem statement

According to the conditions of agriculture in Sichuan province, there are three cropping patterns: single-, double- and triple-cropped lands. The economic benefit and ecological benefit of different crop combinations are different from each other. Relative to single- and double- cropped lands, due to overcropping, the triple-cropped land has high economic benefit as well as great negative effects including reduction in soil fertility and so on.

In a single-cropped land, the farmers have a number of alternative crops from which they can cultivate one crop in a year, such as wheat, maize, potatoes and so on. Similarly, they have many combinations of crops for double- and triple-cropped lands. wheat-maize pattern, wheat-maize-potatoes pattern and wheat-maize-beans pattern are common cropping patterns of dry land circular economy system of crop combinations for triple-cropped lands. The number of crop combinations selected for these three land types are 4, 4 and 2, respectively (Tab. 1). Due to the unconsistency of corp unit area yield and revenue, the farmers prefer to plant the kinds of high profit crops which is commonly low level of yield. One should model the crop-planning problem in order to make a balance between the maximization of revenue and the crop yield.

Table 1. The number of crop combinations selected for these three land types

NO	Single-cropped land	Double-cropped land	Triple-cropped land
I	wheat	wheat-wheat	wheat-maize-potato
II	maize	wheat-maize	wheat-maize-soybean
III	potato	wheat-potato	–
IV	soybean	wheat-soybean	–

2.2 The mathematical model

As mentioned in section 2.1, this section can build the optimal model of dry land multiple-cropping circular economy system. The objective functions and constraints can be designed as follows:

Objective functions

(1) The annual net revenue. The objective function is to maximize the total annual net revenue that can be obtained from cropping in a year. So we have

$$\max\ f_1(x) = \sum_i \sum_j \sum_k b_{ijk} x_{ijk} \quad (1)$$

where k is the index of land type, $k = 1, 2, 3$; j is the index of crop combination, for single-cropped land $(k = 1), j = 1, 2, 3, 4$, for double-cropped land $(k = 2), j = 1, 2, 3, 4$, for triple-cropped land $(k = 3), j = 1, 2$; i is the index of crops in crop combination, for single-cropped land $(k = 1), i = 1$, for double-cropped land $(k = 2), i = 1, 2$, for triple-cropped land $(k = 3), i = 1, 2, 3$; b_{ijk} is the net revenue coefficient that is the benefits that can be obtained per unit area of land from crop i of crop combination j in land type k; x_{ijk} is the area of land to be planted for crop i of crop combination j in land type k.

(2) The total crop yields maximization. This objective function is to maximize the sum of production of crop in a year. So we have

$$\max\ f_2(x) = \sum_i \sum_j \sum_k a_{ijk} x_{ijk} \quad (2)$$

where a_{ijk} is the yield coefficient that is the amount of production per unit area of crop i of crop combination j in land type k.

Constraints

(1) The planting area constrains. The sum of land areas used for a given type of land must be less than or equal to the total available land of that type. So we have

$$\sum_i \sum_j t_k x_{ijk} \le l_k \qquad \forall k = 1, 2, 3 \quad (3)$$

where t_k is the coefficient of land type; $t_1 = 1$ for single-cropped land because no area is shared with other crops; $t_2 = 1/2$ because the same land is being used by two consecutive crop in a year in double-cropped land; $t_3 = 1/3$ because the same land is being used by three consecutive crops in a crop year in triple- cropped land; l_k is the available area of land type k.

(2) The capital constrains. The total amount of money that can be spent for crop production must be less than or equal to the capital available. So we have

$$\sum_i \sum_j \sum_k c_{ijk} x_{ijk} \le c \quad (4)$$

where c_{ijk} is the cost coefficient that is the cost of production per unit area of crop i of crop combination j in land type k; c is the available social capital, this indicates the total amount of money that can be invested for cropping.

(3) The multiple crop land constrains. The areas used for any crop under a crop combination for double- or triple- cropped land must be equal for each crop. For double-cropped land, we have

$$x_{1jk} - x_{2jk} = 0 \quad (5)$$

where the subscript 1 is the first crop of combination j for the double-cropped land, and the subscript 2 is the second crop of combination j for the double-cropped land.

For a given crop combination j, there are only two kinds of crops. As shown in Tab. 1, for example, the subscript 1 means the wheat and the subscript 2 means the the maize for $j = 2$.

Similarly, for the triple-cropped land, we have

$$x_{1jk} - x_{2jk} = 0, \quad x_{2jk} - x_{3jk} = 0 \quad (6)$$

where the subscript 1 is the first crop of combination j for the triple-cropped land, the subscript 2 is the second crop of combination j for the triple-cropped land and the subscript 3 is the third crop of combination j for the triple-cropped land.

As shown in Tab. 1, for example, for a given crop combination $j = 1$, the subscript 1 means the wheat, the subscript 2 means the maize and the subscript 3 means potato.

(4) Non-negativity constraint. The areas used for any crop under a crop combination must exceed 0. So we have

$$x_{ijk} \geq 0$$

3 Analysis

This section focuses on the illustrative case example for the model of dry land multiple-cropping circular economy systems. Section 3.1 firstly use ε - constraint method and convert the multi-objective programming to a linear programming. Then section 3.2 develops the real-coded genetic algorithm (RCGA) and its steps to obtain an optimal solution for the optimal model of dry land multiple-cropping circular economy systems. Finally, the illustrative case example based on the conditions of Sichuan province is given by using RCGA (real-coded GA) in section 3.3.

3.1 Model transformation

In China, because of the large population and farmland shortage, grain yield is a very important factor that affect the socioeconomic development. For ensuring the food of the nation and stability increase in economics, it is necessary to ensure the stable growth of grain yield. Due to the unconsistency of corp unit area yield and revenue, the farmers prefer to plant the kinds of high profit crops which are commonly low level of yield. So the government usually makes some related policies to ensure the stable growth of grain yield. To solve the problem, we use ε - constraint method and assign an value ε to the Eq. (2) and convert it to a constraint:

$$\sum_i \sum_j \sum_k a_{ijk} x_{ijk} \geq \varepsilon \tag{7}$$

where ε is the minimum crop yield that ensure the food of nation every year.

Eq. (7) means that the total crop yield in a year must exceed the minimum crop yield. By converting the Eq. (2) to a constraint, we can get Eq. (8) by having the Eq. (1) as the objective function and Eq. (3) $\sim$ (7) as constraints.

$$\begin{cases} \max z = \sum_i \sum_j \sum_k b_{ijk} x_{ijk} \\ \text{s.t.} \begin{cases} \sum_i \sum_j \sum_k a_{ijk} x_{ijk} \geq \varepsilon \\ \sum_i \sum_j t_k x_{ijk} \leq l_k & \forall k = 1,2,3 \\ \sum_i \sum_j \sum_k c_{ijk} x_{ijk} \leq \text{c} \\ x_{(i1)jk} - x_{(i2)jk} = 0 & \text{for } k = 2 \\ x_{(i1)jk} - x_{(i2)jk} = 0 & \text{for } k = 3 \\ x_{(i2)jk} - x_{(i3)jk} = 0 & \text{for } k = 3 \\ x_{ijk} \geq 0 \end{cases} \end{cases} \tag{8}$$

3.2 GA-based solution approach for the optimal model of dry land

The problem is solved by using a real-coded Genetic Algorithm. This approach, instead of using a binary-coded GA, is more appropriate for real values as it avoids transformation of real values into binary values and then, after crossover and mutation, retransformation of binary values back into real values[5].

In the problem, the algorithm takes the coefficient of crop yield, net revenue, cost and so on as inputs. A population of land area for each kind of crop is created taking into account the constraint of the practical significance of the problem. The initial population is gradually improved by selection and application of genetic operators during the optimization. After 400 generations, the algorithm converges and we get the final optimized population. The general scheme of the genetic algorithm for optimal model of dry land is summarized as follows:

(1) Representation of chromosomes: The chromosome is coded in the form of a vector of real numbers. The vector of real numbers includes the decision variables that define land area for each kind of crop i of crop combination j for land type k. An initial parent population of N chromosomes is created randomly using uniform distribution. The initial population of chromosomes is randomly generated under the constraints of non-negative values and the maximum value of the adequate land.

(2) Fitness function evaluation: Since the objective function is to maximize the annual net revenue, the annual net revenue is the only fitness measure without considering combining the different fitness measures into a real value by using weights or factors. In our GA, we employ Eq. 1 to evaluate the annual net revenue for each individual. Obviously, the higher the annual net revenue, the better the corresponding chromosome.

(3) Selection: The selection mechanism in GA simulates the evolutionary process; namely, the best chromosomes get more copies, the average ones stay even, and the worst ones die off. The first step consists of calculating the objective function value which is the annual net revenue at every chromosome. After normalizing fitness, the selection mechanism in our GA used a roulette wheel mechanism for selecting individuals for reproduction. The individual of each segment containing the drawn number is selected. This operation is repeated as many times as required by the size of the population.

(4) Crossover: Those individuals, that survive the selection step, undergo the alternation by two genetic operators, namely, crossover and mutation, to generate the individuals in the next generation. The crossover operator then combines two chromosomes (parents) to produce two new chromosomes (individuals). The crossover rate deciding pairs of individuals among all the individuals in the population is 0.3 in our GAs.

(5) Mutation: This operator changes the value of a chromosome, which brings the diversity among the population. Whether a chromosome will be modified by a mutate operator or not, is independently decided. For each chromosome a random number between 0 and 1 is generated and if this number is greater than the mutation rate at that time, then the chromosome will be replaced by a random choice of one of the most frequently occurring values. In our GA, the mutation rate is 0.2.

(6) Termination conditions: The processes of generating new chromosomes and selecting those with better function values are continued until the termination conditions are satisfied. The stopping criterion generally used is the maximum number of generations $Gen_{\max}$, set at the beginning of the algorithm. We retain this idea to control the GA: our GA terminates after 400 generations.

Based on above discussions, the implementation structure of RCGA for our model is described as follows:

Procedure `The GA algorithm for optimal model of dry land`

Step 1. The land area for each kind of crop is represented as a N dimensional vector Ch_r;
Step 2. Set the generation counter to zero, $n = 0$;
Step 3. Using uniform distribution, randomly generate initial population gen(0) of trial vectors Ch_r for $r = 1, 2, \cdots, N$ from a feasible range in each dimension;
Step 4. Evaluate fitness of each individual of current population by using the fitness subroutine;
Step 5. Increase the generation counter by one, $n = n + 1$;
Step 6. Apply GA to produce gen($n + 1$): preserve the elite chromosomes, select parents from population of trial vectors using tournament selection, recombine them using crossover and mutation operators to produce child vectors;
Step 7. Evaluate fitness of each chromosome of current population by using the fitness subroutine and store the solution corresponding to the best fit chromosome;
Step 8. Apply the replacement operator and diversity mechanism to the current population;
Step 9. Check for the convergence criterion: if current generation number n is equal to Gen_{max}, stop and print the results such as the land area for each kind of crop and the annual net revenue, corresponding to the best fit vector of the population. Otherwise, go to step 6;

3.3 An illustrative case example

In Sichuan Province, the main grain crops of dry land multiple-cropping circular economy systems and the common cropping patterns are shown in Tab. 1. The data required for the models like area, yield , cost of production, net revenue, minimum crop yield of the crops for different crop combinations in different land types are shown in Tab. 2. For numerical analysis, the values are the averages of the values of these parameters for the statistic data analyzed by [12, 13] and Sichuan Statistic Yearbook (2007). In fact, the crop yield per unit area, cost per unit area, and net revenue per unit area which vary with the change of the external environment can not be the fixed values. So it is necessary to list the variation range of these parameters in Tab. 2 according to [12, 13]

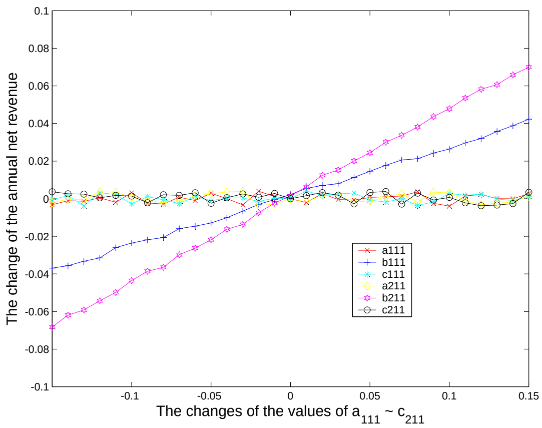

Fig. 1. Parameter sensitivity of the annual net revenue to the changes in the values of $a_{111} \sim c_{211}$

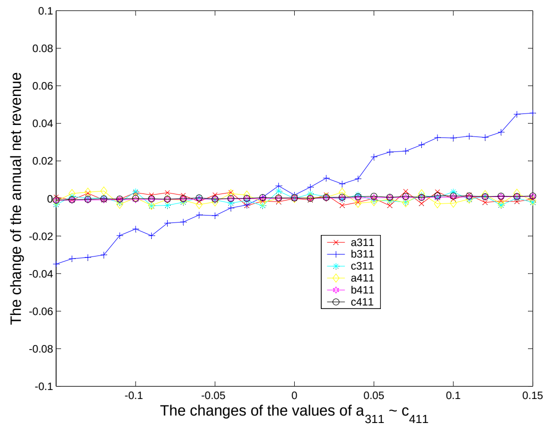

Fig. 2. Parameter sensitivity of the annual net revenue to the changes in the values of $a_{311} \sim c_{211}$

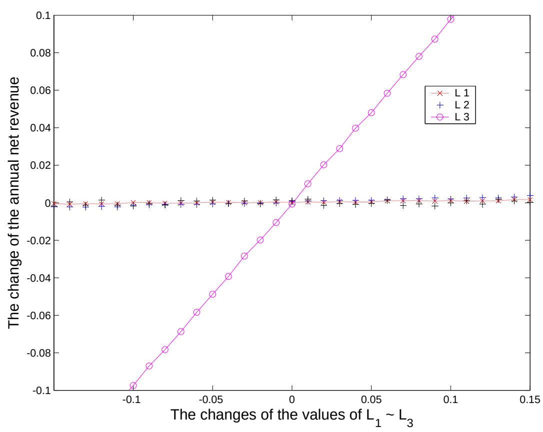

Fig. 3. Parameter sensitivity of the annual net revenue to the changes in the values of $L_1 \sim L_3$

The total amount of money that can be invested for cropping is 9645 million yuan. The minimum crop yield in a year is 18.1 million ton. The available single-cropped land area is 0.172 million ha; The available double-cropped land area is 0.378 million ha; The available triple-cropped land area is 1.412 million ha. The present model consists of 18 variables and 31 constraints. According to the model (8), using the previously stated set of parameter values, the optimal available land areas for different crop combination for the respective land type are obtained in Tab. 3. It is obvious that wheat-maize- soybean pattern and wheat-maize-potato pattern for triple-cropping, wheat-soybean pattern for double-cropping, soybean pattern for single-cropping are the main cropping patterns. The annual net revenue is 8294.91 million yuan. In order to examine the effect of these parameters including the coefficient of crop yield per unit area (a_{ijk}), the coefficient of net revenue

Table 2. The yield, cost of production, net revenue of Sichuan's crops in 2003

	Crop	Yield (kg/ha)		Cost of production (yuan/ha)		Net revenue (yuan/ha)	
		average	range	average	range	average	range
1	wheat	3277	2785.4∼ 3768.5	1808.7	1537.3 ∼ 2080.0	1566.9	1331.8 ∼ 1801.9
2	maize	4568	3882.8 ∼ 5253.2	2062.9	1753.5∼ 2372.3	2824.95	2401.2∼ 3248.6
3	potato	9402	7991.7 ∼ 10812.3	1886.8	1603.8∼ 2169.8	3002.55	2552.1∼ 3452.9
4	soybean	1016	863.6 ∼ 1168.4	1022.8	869.4 ∼ 1176.2	1556.7	1323.1 ∼ 1790.2

Note: for simplicity, we set the yield , cost of production, net revenue of the crops for different crop combinations in different land types as the same.

Table 3. Solutions for different cropping patterns

Land type	Solutions	Land type	Solutions
wheat	0	wheat-wheat	0
maize	0	wheat-maize	0
potato	0	wheat- potato	0
soybean	17200	wheat- soybean	37800
wheat-maize-potato	578953.8455	wheat-maize- soybean	833246.15

per unit area (b_{ijk}), the coefficient of cost per unit area (c_{ijk}) on the annual net revenue, we numerically solve model (8) to determine the optimal results under a set of values for the parameters mentioned above. We vary them over a reasonable range in the sensitivity analysis and obtain the optimal annual net revenue. Figs. 1∼ 3 provide a feel for how sensitive the annual net revenue is to the changes in the values of the coefficient of crop yield, the coefficient of net revenue per unit area, the coefficient of cost and so on. Figs. 1∼ 3 suggest the following: (1) The increase of the annual net revenue increases with the coefficient of net revenue per unit area. Remarkably, the variation of b_{211} is wider than the other three coefficients of net revenue per unit area. (2) The increase of the annual net revenue increases sharply with the increase l_3. Meanwhile, with the increase of l_2 and l_1, the change of the annual net revenue fluctuates up and down around 0 because the large proportion of the cultivated land is the triple-cropped land. (3) No matter how the the coefficient of crop yield and cost change, the change of the annual net revenue fluctuates up and down around 0. Besides, the change of the minimum crop yield also has no obvious influence on the annual net revenue.

4 Conclusions

This paper builds an optimal model of dry land multiple-cropping circular economy system of Sichuan province involving multiple conflicting objectives to solve crop planning problem. In consideration of the complexity and conflict between the objectives, we use ε - constraint method and convert the multiple objectives problem to a single objective linear programming. Compared with the present data, the converted model offers an optimal solution. Moreover, all the parameters of the problem need to be specified precisely in the planning environment and fixed in the analysis above. However, in fact, in most of the practical decision problems, they are often imprecisely defined due to the expert's ambiguous understanding of the nature of them. So in the further research, to overcome the above difficulty, we will think over introducing the fuzzy goal programming approach to crop planning problems in the environment of crisp resource constraints.

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