A regulation-allocation coupling approach for agricultural water resources management based on water quantity orientation

Siyuan Liu, Ni Wang, Jiancang Xie, Rengui Jiang and Menglong Zhao

ABSTRACT

In water-scarce areas with low grain yields, people have to expand the farmland scale to gain more food. Rapid expansion of agricultural scale may lead to a higher risk of re-abandonment of wasteland due to waterless irrigation in water-deficient areas. Against this background, this study proposed a water resources regulation-allocation coupling model. The 'regulation' is to control the water consumption of agriculture and regulate the utilized scale with water resources as the main constraint; the 'allocation' is to optimize the water resources allocation among crops and arrange the crop planting system according to the water quota for different crops and the economic, social and ecological benefits brought by crops, so as to control the water resources among crops. Afterwards, taking an agro-pastoral ecotone in Northwest China as the study case, schemes of feasible agricultural scale and planting structure suitable for local conditions were obtained. Lastly, the matching patterns of land and water resources were raised gradually from 'poor' into 'good' degree from 2015 to 2030. This study is expected to provide a reference for controlling the ordered and balanced development of land and water resources of agriculture as well as effectively improving the sustainable development ability in water-deficient areas.

Key words | agricultural development scale, agricultural water management, cropping scheme, optimization, water resources regulation-allocation model

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HIGHLIGHTS

- A water resources regulation-allocation coupling model involves two methodologies of 'top-down' and 'bottom-up' is proposed to regulate the scale of agricultural sandy land.
- Amount control and structure optimization help to improve water resources utilization efficiency and the matching degree of water and land resources.

INTRODUCTION

Water crises and food insecurity occurs all around the world, especially in developing countries, attributed to the population expanding, industrialization, and improved living standards (UNEP 2011; FAO 2014). A quarter of the world's population is facing a critical, chronic problem of water shortage, and increasing water demands due to future population growth aggravate the problem, which needs resolution (Kondili *et al.* 2010). Globally, agriculture is the largest consumer of water resources. Consequently, water scarcity and yield reduction could heavily impact agricultural production and may result in a decline in food security worldwide (Olesen & Marco 2002). In water-scarce areas, to a certain extent, because of insufficient water resources and low food production, people have to reclaim more uncultivated land, which may lead to more water consumption in agriculture, which then falls into a

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vicious circle. Then comes the continued deterioration of the ecosystem.

Hence, improvements and measures for agricultural water management are necessary. Traditionally, optimization of irrigation systems and water resource allocations through appropriate multi-cropping patterns and irrigation scheduling are considered as crucial responses to address water scarcity (Moradi-Jalal *et al.* 2007; Sadati *et al.* 2014). Several researchers have developed optimization models for planning and management of agricultural water. Maqsood *et al.* (2005) developed an interval-parameter two-stage optimization model and applied it to allocate water from a reservoir to three farms cropped with alfalfa, wheat, and potato. Ghahraman & Sepaskhah (2002), for example, developed a stochastic dynamic programming optimization model for the optimal allocation of water to a predetermined multiple cropping pattern in Iran. Nagesh Kumar *et al.* (2006) also proposed an irrigation allocation model to determine relative yield under a specified cropping pattern in Karnataka State, India, using a genetic algorithm (GA). Similarly, Georgiou & Papamichail (2008) developed a non-linear programming optimization model to determine the optimal reservoir release policies and the optimal cropping pattern in Chalkidiki region, Greece. Xia (2012) introduced a maximum available water resources assessment based on water quality objectives and system constraints through a workable integrated water quality and quantity model, with respect to providing useful information to support decision making concerning allocation of the available water resources. Meena *et al.* (2019) proposed a regulated deficit irrigation management strategy for wheat under various schemes for efficient water use in sandy land in water-depleting regions.

Generally, traditional agricultural water supply planning and management is based on fixed water requirements and the mechanisms necessary to deliver the water to meet water demand (Molinos-Senante *et al.* 2014), which is to balance water supply and demand. For the sake of food security and economic development, various methods and measures have been put forward to meet the water demand for agriculture. Most of them are kind of 'demand-oriented' water resource management strategy, which focuses on maximization of satisfying water demand and optimizing water distribution. However, in the face of increasing water demand, the crisis of total water resources is still an urgent problem to be solved.

In order to alleviate the contradiction between supply and demand of water resources and improve the water utilization rate, various water-saving measures have been invented and implemented, especially in irrigation systems. However, it could be expected that no matter how effective the water-saving measures are, with the expansion of cultivated land and irrigation scale, the total amount of agricultural water consumption will keep rising. Additionally, in water-scarce areas with low grain yields, people have to expand the farmland scale to gain more food. Rapid expansion of agricultural scale may lead to a higher risk of re-abandonment of wasteland due to waterless irrigation in water-deficient areas.

Against this background, a 'water amount-oriented' model was proposed in this study. Retaining the optimal allocation of water resources in traditional agricultural water resources management, this model will also adopt control of the development of users' water demand under the constraints of available water resources; that is, limiting the scale of the water consumption sector. The main method is to develop a Water Resources Regulation–Allocation Coupling Model (WRACM) involving two methodologies of 'regulation' and 'allocation'. The 'regulation' is to control the water consumption of agriculture and regulate the utilized scale with water resources as the main constraint; the 'allocation' is to optimize the water resources allocation among crops and arrange the crop planting system according to the water quota of different crops and the economic, social and ecological benefits brought by crops, so as to control the water resources among crops. The goal of the model is to realize the most efficient utilization of water resources in the case of a limited total amount, so as to reach the maximum threshold of grain production. The proposed model is expected to be a useful tool for supporting the decision process of agricultural water resources planning and management in areas of water scarcity, contributing to alleviate the water shortage crisis.

As a typical representative, China has experienced severe water shortage, especially in the northwest. The agro-pastoral ecotone of Northern Shaanxi Province (ANS) is located in the arid area of Northwest China and in the southern margin of Mu Us Sandy Land (one of the four major sandy lands in China). The land in this area has not completely degraded into desert, and the population distribution is relatively dense (Wang *et al.* 2013, 2014). In virtue of drought, water shortage and desertification, the grain yield of ANS is at a low level all year round. In order to gain enough food, the people actively reclaimed new land and turned it into arable land. From 2010 to 2018, the scale of arable land increased by almost 10 thousand hectares (Shi *et al.* 2019), which has exacerbated the shortage of water resources and deteriorated fragile ecosystems. Taking ANS as the study case, with the amount of available water resources as the main constraint, this study utilized the WRACM model to determine the maximum threshold of cultivated land scale and the allocation scheme of water resources among crops, in order to provide a reference for water resources management and sustainable development of an ecosystem.

DESCRIPTION OF THE CASE STUDY

Study area

The agro-pastoral ecotone of Northern Shaanxi Province (ANS) in China is taken as the study area here, which is located in northwest China (ranging from 107°35′ to 111°29′E and from 37°35′ to 39°02′N) with an approximate area of 33 992 km^2 (Figure 1), and consists of six counties including Yuyang, Shenmu, Fugu, Hengshan, Dingbian, Jingbian. The Mu Us Desert lies to the north and a loess plateau lies to the south of the region. The area has a typical continental semi-arid climate. The water resources in this region are very poor, with a per capita water resource of only 9.97 million m^3, which is lower than the standard of water resources in severely water-scarce countries proposed by the United Nations Population Action Organization in 1993 of less or equal to 10 million m^3/per capita. Agriculture, as the largest water sector, accounts for 63.1% of total water consumption on average. The lack of water resources has seriously restricted the development of local agriculture.

As the geographical location is close to the southern margin of Mu Us Sandy Land, more than 44.2% of this area is desertified land. In recent years, as urban expansion and industrial development have occupied agricultural land, in order to increase grain production, the government has taken a large number of water-saving measures to encourage farmers to develop sandy agriculture on unused sandy land. Therefore, sandy land agriculture scale ushered in rapid expansion in this area, and agricultural water consumption has also witnessed a sharp increase.

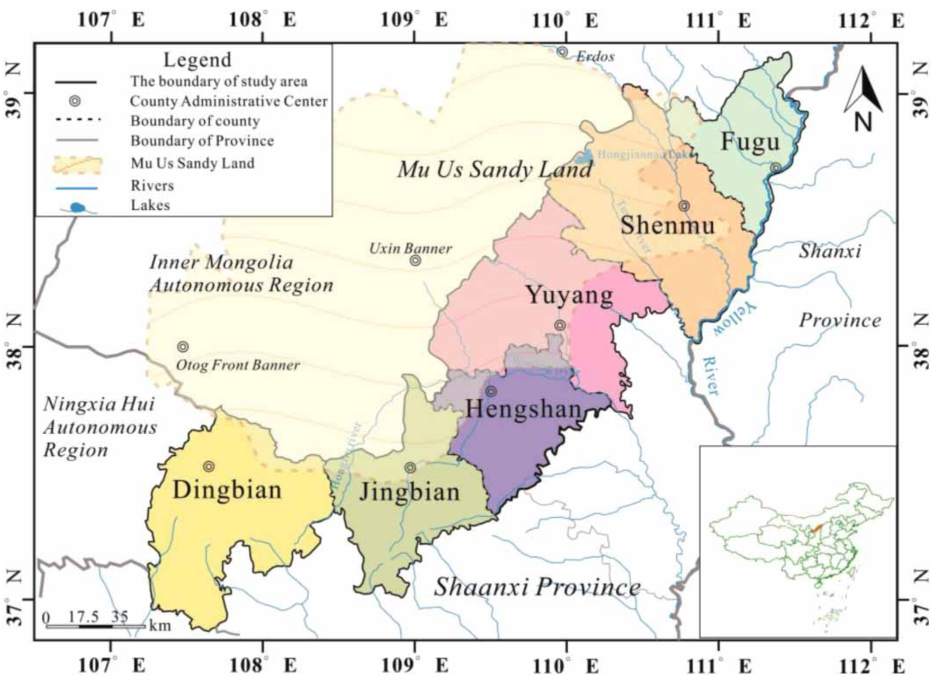

Figure 1 | The location of agro-pastoral ecotone of Northern Shaanxi Province of China.

Scenarios setting for cropping sturcture

With arid climate and concentrated rain and heat, the suitable crops for growth in ANS are grain crops (mainly maize), economic crops (mainly potato), as well as various drought-tolerant forage crops (mainly Astragalus). In order to meet the development requirements of regional crop diversity, food crops, economic crops and forage crops are considered to meet the needs of food security, economic progress and animal husbandry development respectively. In the process of calculation, different scenarios are generated by planting diversified crops.

Varied crop combinations are primarily composed of the unitary cropping system (CS-1) of 'Grain Crop (GC)', 'Economic Crop (EC)', 'Forage Crop (FC)', a two-component cropping system (CS-2) of 'GC + EC', 'GC + FC', 'EC + FC' and the three-component cropping system (CS-3) of 'GC + EC + FC'. The distinct planting schemes provide seven scenarios for each county. The maximum exploitable scale of each scenario and the allocation of inter-crop water resources are calculated by the WRACM model, and the recommended schemes are selected conditionally. The specific scenarios are as followed Table 1:

METHODOLOGY

The framework of water resources regulation-allocation coupling model

Optimal objectives

The proposed mathematical model WRACM involves two methodologies of 'Regulation' and 'Allocation', which corresponds to the main means of the model: the maximum utilization scale of agricultural land, and the water resources allocation for crops on an irrigated area. The core of 'Regulation' is the theory of water-based development; that is, 'scale determined by water'. This is not only the constraint of water resources on the development of various industries, but also a new concept for water use. Water-based development is a strategic water saving, as development must be sustainable development in accordance with the laws of nature, and water is the basic factor for human survival and development.

Facing the abnormal situation of drought and flood caused by water shortage, it is an important strategy for us to plan for the future, to take precautions and determine development scale by water. In a typical arid and water-scarce area, it is necessary to strictly control the agriculture utilized scale under limited water resources, thus to prevent the excessive exploitation of water resources and environmental deterioration which was led by the scale from blind expansion. In this study, water resources are taken as the main constraint to control the water consumption of agriculture through regulating the utilized scale and obtain the optimal water allocation.

Reasonable agricultural planting structure is conducive to controlling water consumption within a certain range through an appropriate water-saving irrigation system and cultivation system. This is a bottom-up way to control water. The 'Allocation' is to optimize the water resources distribution among crops and arrange the crop planting structure, according to the water quota for different crops and the economic, social and ecological benefits brought by crops, so as to control the water resources among crops.

The concepts of 'Regulation' and 'Allocation' are coupled into a multi-objective optimization model with three objectives of economic, social and ecological benefits. The goal of the model is to maximize the benefits obtained from the use of water and to determine a feasible agriculture scale and crop planting distribution. Hence, three sub-functions of maximizing economic benefits, social benefits and ecological benefits are constructed to quantitatively express the maximum thresholds that could be supported with the restriction of limited water resources availability. The planting area of crop i is selected as decision variable x of the model.

Objective 1: Economic benefits

Table 1 | Multivariate scenarios based on cropping system

Scenario	Cropping system	Crop		
		Maize	Potato	Astragalus
CS – 1	GC	√	×	×
	EC	×	√	×
	FC	×	×	√
CS-2	GC + EC	√	√	×
	EC + FC	×	√	√
	GC + FC	√	×	√
CS-3	GC + EC + FC	√	√	√

The function of economic benefits to be maximized is the difference between total income and total cost, which represents the net benefits achieved by deducting costs from income derived from crop harvesting. The objective 1 is as below:

$$f_1(x) = \max\left\{\sum_{i=1}^{I}\sum_{j=1}^{J}(\rho^{\pm}_{AVG,i}\cdot Y_{\max,j} - \sum_{j=1}^{J} IRRIG_{i,j}/\eta_j \cdot C^{\pm}_{AVG,i} - \sum C)\cdot \sum_{j=1}^{J} x_{i,j}\right\} \quad (1)$$

where, $x_{i,j}$ is the plant area of crop species i irrigated by water source j, $i = 1, 2, 3$, $j = 1, 2, 3\ldots5$; $\rho^{\pm}_{AVG,i}$ denotes the average market price of crop I; $C^{\pm}_{AVG,j}$ represents the cost of irrigated water from water source j; $Y_{\max,j}$ represents the yield of crop i; $IRRIG_{i,j}$ is irrigation water of crop i from water source j; η_j is the water efficiency of source j; $\sum C$ denotes other operating costs per unit area, including transportation costs, agricultural irrigation machinery costs, crop fertilization costs, labor costs and others.

Objective 2: Social benefits

The most effective advantage brought by the increase of farmland area for society and the surrounding residents is the resettlement of the labor force.

$$f_2(x) = \max\left\{\sum_{j=1}^{J}\sum_{i=1}^{I} x_{i,j}/\phi_{Labor}\cdot\tau\right\} \quad (2)$$

Here, the social benefits brought by the development and utilization of sandy land are measured by the benefits of labor resettlement. Among them, ϕ_{Labor} is the number of resettable labor force per hectare. τ is the disposable income of agricultural workers.

Objective 3: Ecological benefits

Improvement of the ecological environment is a necessary means to realize sustainable development in water-deficient areas. The value of ecological services (ESV) is widely recognized as an effective method to evaluate ecological benefits (Shi *et al.* 2015; Xie *et al.* 2017). In this study, the value of ecological services was calculated based on the method of ecological green equivalent and equivalent factor method.

Ecological green equivalent is developed based on measuring the ecological compensation ability. Ecological compensation is made by natural ecosystems for ecological damage due to social and economic activity (Shi *et al.* 2015). Forest, as the backbone of the Earth's terrestrial ecosystems, has multiple functions such as water conservation, soil and water conservation, climate improvement, atmospheric adjustment, air cleaning and biodiversity conservation (Jim 2001). The 'green equivalent' means that an equal amount of photosynthesis, and suitable layout, are ensured to compensate for the regional ecological functions played by a certain amount of forest vegetation.

Then, the equivalent factor method, which belongs to the unit value-based approach (Costanza *et al.* 1997), developed by Xie *et al.* (2003) is widely used, especially for the ecosystem service value (ESV) evaluation results from land use changes. For this method, the economic value of each ecosystem service from an ecosystem is estimated as the product of an equivalence coefficient (dimensionless) and the economic value (expressed as $/hectare) represented by one standard equivalence factor, which is the value of the product or service provided per unit area.

Combined with the eco-value coefficient of unit area on the theoretical basis of ecological service function of Costanza *et al.* (1997) and Xie's (2003) research, the formula for calculating the value of ecological assets is as follows:

$$ESV_i = ESV_{forest}\times V_{total}\times X_k \quad (3)$$

where, ESV_k is the ecological assets of k ecosystem; ESV_{forest} indicates the value of the ecological assets per unit area of forest ecosystem, and X_k denotes the area of k ecosystem.

Then, the ecological benefit formula could be expressed as:

$$f_3 = \max\{\triangle ESV\} = \max\left\{\sum_{k=1}^{K}(ESV'_k - ESV_k)\right\} \quad (4)$$

Here the $\triangle ESV$ represents the added value of ecological services.

Constraints

Constraint of water resources

A two-tier constraint is established as the water resource constraint according to the amount of the total available water resources and requirements of local water management system. With this constraint, the water consumption of agricultural development and utilization area of newly added sandy land should not exceed the minimum of the two-level constraint.

$$\sum Q_{sa} = \sum_{i=1}^{I}\sum_{j=1}^{J} IRRIG_{i,j}\cdot x_{i,j} \le \min \left[\sum_{j=1}^{I}(Q_T - \Delta Q_j),\quad Q_R - \sum_{j=1}^{J}\Delta Q_j\right] \tag{5}$$

where, Q_T (m^3) represents the regional available water quantity, ΔQ_j (m^3) denotes total water demand of other water use industries, Q_R (m^3) is the maximum water use index restricted by regional governments.

Constraint of irrigation water utilization coefficient:

$$\eta_j \ge [\eta_R,\ \eta_R'] \tag{6}$$

The irrigation water utilization coefficient needs to meet the goals of regional management requirements, where, η_R and η_R' are the control coefficients from the strictest water resources management system and the target of regional water resources planning respectively.

Constraint of cultivated land resources

$$X \le \sum A_{us} \tag{7}$$

$\sum A_{us}$ (ha) is the total area of undeveloped sandy land in the study area. The final constraints are variables that represent non-negative constraints.

The matching coefficient of agricultural water and land resources

The matching coefficient of water and land resources is an effective means to test the degree of adaptability between available agricultural water and cultivated land scale in a region. At the same time, the effect of the model proposed in this study on regional agricultural water resources management could be reflected with the matching coefficient to a certain extent. The matching coefficient of water and land resources (R_i) is proposed by Liu *et al.* (2006) and has been proved to have good adaptability in water-deficient areas (Bai *et al.* 2017; Liu *et al.* 2018). This is an indicator to reflect the spatial-temporal proportion of water supply and cultivated land resources in a specific zone. The matching coefficient of agricultural water and land resources is determined by regional water resources, arable land resources and the spatial and temporal distribution and utilization characteristics of water resources. The larger the value, the higher the degree of satisfaction of water resources to cultivated land resources. On the contrary, a lower degree of satisfaction indicates that the situation of agricultural resources in this area is one of abundant land and deficient water. The matching coefficient model of agricultural water and land resources is as follows:

Computing model of matching coefficient of agricultural water and land resources of county-level areas

$$R_{i,k} = W_{i,k}\cdot \overline{\partial_{i,k}}/L_{i,k} \tag{8}$$

where, $R_{i,k}$ is the matching coefficient of agricultural water and land resources of i county in k year; $W_{i,k}$ is the total water resources amount (10^4 m^3) of i county in k year; $\overline{\partial_{i,k}}$ is the average ratio of agricultural water use of i county in k year; $L_{i,k}$ is the available agricultural acreage of i county in k year.

Computing model of matching coefficient of agricultural water and land resources of regional level areas

$$R_k = \sum_{i=1}^{n}(R_{i,k})/n \tag{9}$$

where R_k is the regional matching coefficient in k year; n is the number of counties of this region. The others are the same as above.

According to different values of R_i, the matching degree of water and land resources in water-deficient areas is classified into five grades, as Table 2.

Table 2 | The grades of the matching degree of water and land resources

Index	Ranges				
R	0.73 ~ 11.73	0.20 ~ 0.73	0.16 ~ 0.20	0.12 ~ 0.16	0 ~ 0.12
Degree	Excellent	Good	Medium	Poor	Very poor

RESULTS AND DISCUSSION

Feasible agriculture scale and suitable crop structure

The model was solved by the evolutionary search based non-dominated sorting genetic algorithm (NSGA-II) (Deb *et al.* 2002) with MATLAB software. Since the Pareto optimal solution is a set, the results need to be evaluated. For the sake of better characterizing the boundary threshold of the scale of additional agricultural development supported by water resources, the maximum scale of development is chosen as the recommended scheme here. When water resources are sufficient to support the development of all unused sand, the recommended schemes are CS-3 to ensure the diversity of the crop system.

From a partial point of view, it is worth noting that, among the six counties in ANS, the restraint intensity of Yuyang District is the strongest. Specifically, the area of unused sandy land in Yuyang District was 45,329.2 ha in 2015, and the total area of agricultural development of sandy land could be supported by water resources was 3,496.5 ha, accounting for only 8.1% (Figure 2). The limitation of water resources has seriously restricted the development of sandy land agriculture. This phenomenon has been alleviated only with the increase of water supply in 2030, the proportion of exploitable area reached 91.3% (35,948.9 ha) (Figure 2(c)), but the available water resources still cannot adequately satisfy all the undeveloped sandy land to be fully utilized. The regions with least restrictive water constraint are Fugu and Hengshan, where the water resources are sufficient to support the utilization of all unused sandy land. The next is Dingbian, with 5,765.5 ha unused sandy area in 2015; only 62% of the total can be exploited with the support of water resources, nevertheless then all exploitation of spare sandy land could be realized after 2020 (Figure 2(b) and 2(c)).

From a macroscopic view, according to the land use status and land development plan of ANS, the total area of unused sandy land is 64 274.5, 61,316.8 and 5,474.5 ha in 2015, 2020 and 2030 respectively. The exploitable sandy area that can be sustained by current water resources is only 16,443.4 ha, accounting for 25.6% in total; by 2020, it will increase to 22,637.7 ha, accounting for 36.9%; then, with the massive supplement of water diversion projects and other water sources, the figure will be 51,440 ha and 93.7% by 2030.

Depending on geographical locations and water resources conditions, the sustainable scale of each county varies. Hence it is necessary to formulate development plans according to local conditions. In view of the regions where unused sandy land could not be wholly exploited, such as Yuyang and Jingbian, the development scale of sandy land agriculture should be strictly regulated and controlled to ensure the normal operation of social production and attention shoould be paid to the rational simultaneous utilization of water resources.

Water resources allocation for cropping system

On account of the scale scheme for agricultural development and utilization of sandy land in ANS, the regional remaining available water is allocated accordingly. Under the constraint of available agricultural water resources, the water resources are distributed to the water demand of distinct crops to realize the optimal allocation of water resources in the process of sandy land agricultural development and optimization of the agricultural planting structure.

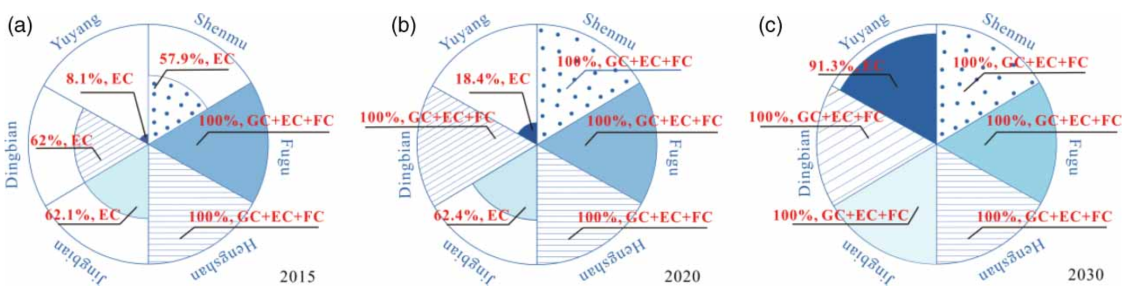

Figure 2 | Proportions of exploitable sandy area and suitable crop structure of ANS.

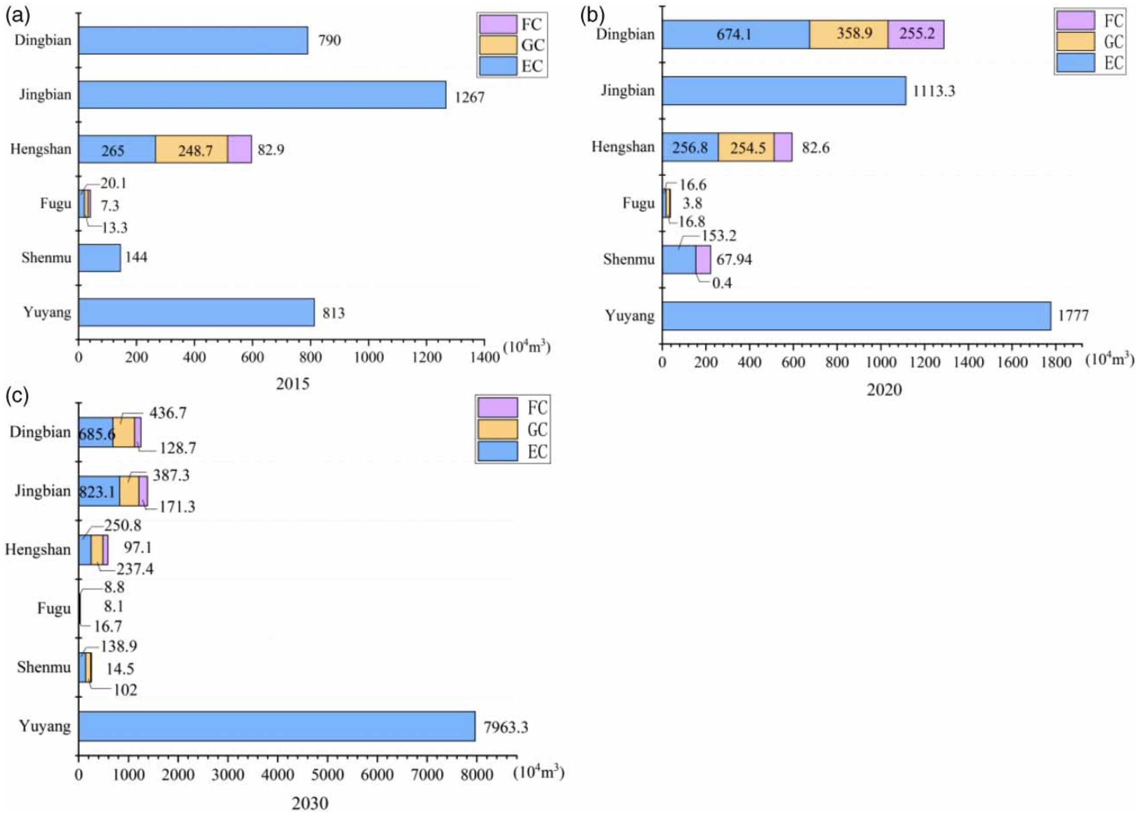

Figure 3 | Water resources allocation scheme among crops in sandy agricultural land of ANS in 2015 (a), 2020 (b) and 2030 (c).

In addition, the sandy land to be utilized is not the original inherent cultivated land of local farmers. In its location at the edge of Mu Us Sandy Land, the surrounding residents scattered in this area mainly planted maize. According to 'Crop Water Requirement and Regional Irrigation Model in Shaanxi Province' (Kang 1992), the water requirement for the whole growth period of maize planted in sandy land of ANS is 4,350 m^3/ha, and the yield is only 5,625 kg/ha. After applying the compound soil technology of Arsenic Sandstone and sand, the irrigation quota of maize decreased to only 2,442 m^3/ha, and the yield also increased by about 1.76 times (Zhao *et al.* 2017). Taking Yuyang as an example, the water resources available for sandy land agricultural utilization in 2015 were 813×10^4 m^3, which could only supply 1,869 ha of maize in the past and now reaches 3,222.4 ha. This further shows that this mode is conducive to the more intensive use and more efficient use of water resources.

On the basis of the water-saving measures implemented formerly, water resources are reasonably distributed among crops with the application of the WRACM model. As indicated in Figure 3, the number of counties with adequate water resources that have the ability to implement the three-component cropping system have changed from two to four and finally to five from 2015 to 2030. It can be inferred that the abundance of water resources is also related to the diversity of the agricultural system. The weaker the water resources restraint capacity is, the stronger the support capacity is, which in turn could satisfy the growth requirements of more crops and exchange for more benefits.

Notably, the water resources in Yuyang District cannot fully satisfy all the unused sandy land to be exploited, so according to the model calculation results, the development scale is the largest and the comprehensive benefit is best when only potatoes are planted (Figure 3). The available water resources for agricultural development in sandy land were adequately utilized in Yuyang District, and there was no surplus water.

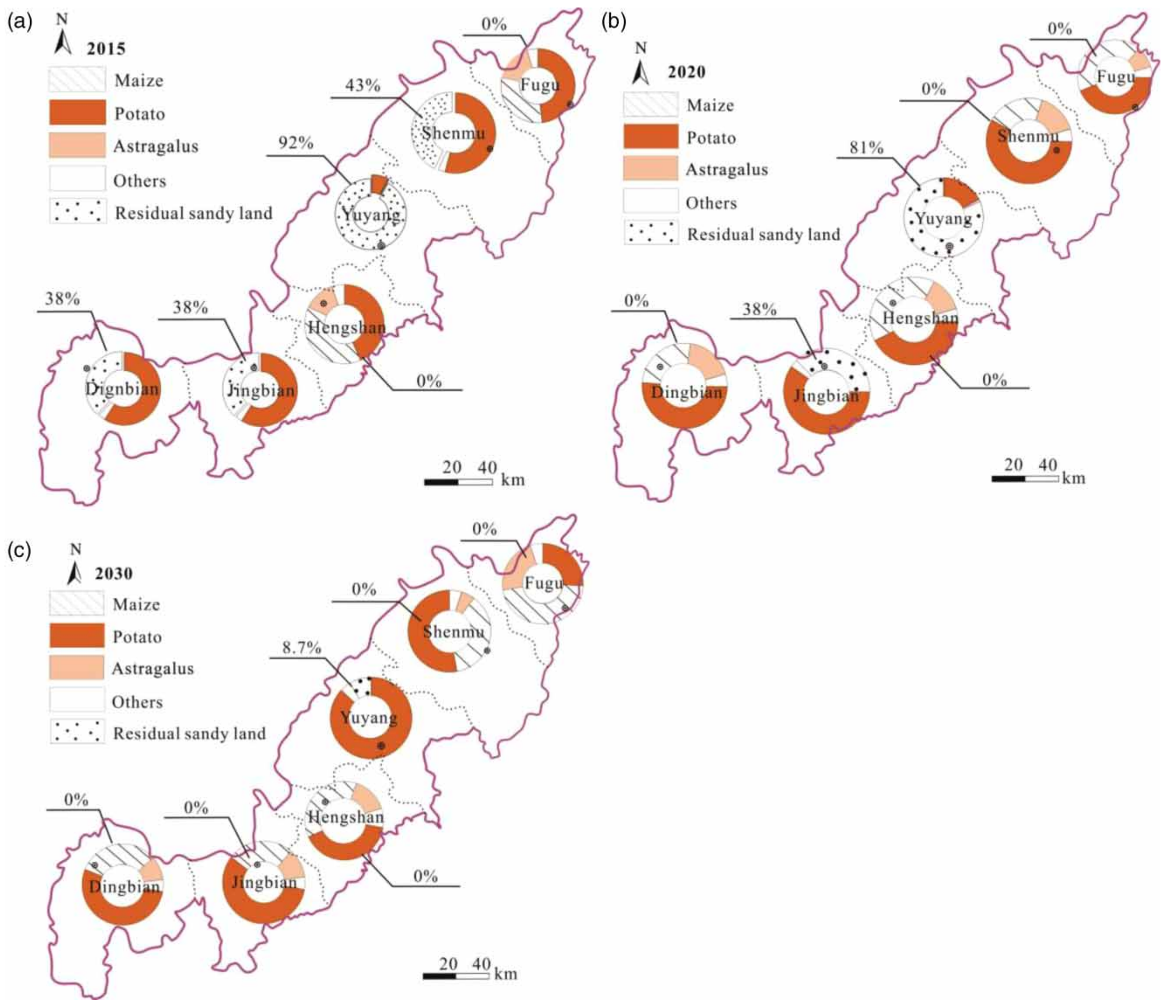

Figure 4 | The variations of the feasible sandy land agriculture scale of ANS in 2015 (a), 2020 (b) and 2030 (c).

Spatial analysis of sandy land agriculture scale

Differing in geographical locations, the six counties in ANS have a certain degree of difference in the distribution of water resources and sandy land. The scale schemes of sandy land agricultural development and utilization under water resources constraints in 2015, 2020 and 2030 in the previous counties and districts have changed spatially with time and conditions (Figure 4).

Overall, in 2020 and 2030, the shortage of water resources in various counties and districts was obviously alleviated due to the new water conservancy projects and water diversion projects, and the exploitation of unused sandy land area showed a gradual increase trend, especially in 2030. The total unused sandy land area of ANS, in line with current trends in 2015, 2020 and 2030, was 64,272.5, 61,316.8 and 54,874.5 ha, respectively, and after exploiting the total remaining unused sandy land area reduced to 47 831.1, 38,679.1 and 3434.51 ha. The proportion of remaining unused sandy land decreased year by year, to 74.42%, 63.08% and 6.26% in 2015, 2020 and 2030 respectively. As can be seen from Figure 4(a), in 2015, there are still four counties whose water resources could not support the full utilization of unused sandy land except Fugu County and Hengshan District. By 2020, it changes to two regions, and by 2030, only Yuyang District is the last one with scarce water resources. In terms of agricultural planting structure, potato cultivation occupies an absolute advantage in the distribution of the cropping system, which is related to the higher yield and economic benefits of potatoes promoted by the natural geographical advantages in ANS.

Among them, the remnant sandy land of Yuyang experienced the biggest fluctuations, from 92% in 2015 to 8.7% in 2030. In 2030, 76 million m^3 of new water was delivered to Yuyang, and the new water conservancy project increased the regional water supply capacity, which greatly alleviated the shortage of water resources. Nevertheless, scarce water is still an inextricable problem to fully support the development and utilization of sandy land, which has an obvious restrictive effect on the scale of development. For example, the cropping system of Shenmu changed from CS-1 to CS-3 after it received the transferred water. With abundant water resources, Fugu and Hengshan have always keep the CS-3 cropping, especially Fugu, where the development of karst water has greatly improved the ability of water resources to support land use. Ultimately, all regions could maintain or gradually transform into ternary cropping structure in the case of sufficient or abundant water resources. To a certain extent, it can be concluded that the diversity of regional development has obvious advantages when the water resources restraint is weak.

Variation characteristics of the matching degrees of water and land resources

The matching degree of sandy agricultural water and land resources in ANS of each county was determined by the matching coefficient calculation model of $R_{i,k}$. In the overall perspective, the matching patterns of land and water resources in ANS area shows a weak attitude in the middle and high in the north and south. This situation just corresponds to the population distribution in ANS, where most of the population is concentrated in the central zone, especially Yuyang. In 2015, the average coefficient of the whole region is 0.15, which is a poor degree; afterwards it raised slightly to 0.18 in 2020, pointing to a medium level; ultimately, it increased to 0.22 and entered a good state in 2030.

Simultaneously, the matching degree of each county differs prominently. Fundamentally speaking, due to the difference of resource endowment and topography, the interaction of water and land resources among the counties and districts results in uneven distribution of time and space. And water consumption in the areas with concentrated population and developed industry occupies agricultural water, which ultimately forms the distinct spatial features of sandy land resources and water resources. According to the calculation results, the prefectures with 'good' matching degree in 2015 are Fugu and Hengshan, and the ones with 'poor' performance are Shenmu, Jingbian and Dingbian, while Yuyang is the only county with 'very poor' performance (Figure 5(a)). Subsequently, Dingbian joined the group of 'good' and Shenmu is very close, with a matching coefficient of 0.19 (Figure 5(b)). The highest promotion was achieved in 2030, when Yuyang entered the ranks of 'medium', and all other counties were matched with 'good' (Figure 5(c)).

Theoretically, agricultural exploitation in sandy land has effectively increased the area of cultivated land, and it is foreseeable that grain production would increase. However, if it is separated from the actual carrying capacity of regional water resources, it will lead to overexploitation of water resources, land degradation and other ecological environment problems, and then change the regional allocation pattern of water and land resources. Consequently, the region of ANS ought to pay more attention to alleviating the shortage of water resources and the mismatch of water and soil resources. In addition to regulating the developing scale of sandy agriculture and allocation of agricultural water resources in sandy land, population and industrial concentration should also be adjusted to adapt to a more harmonious natural and artificial system.

In overview, changing of matching coefficients in current and future years are compared, which proves that the application of the model could effectively improve the matching degree of water and land resources to present a more harmonious agricultural system. This proves the validity of the model to some extent.

CONCLUSIONS

Water resources are the key factors to restrict the scale of agricultural development, and coordinated water resources

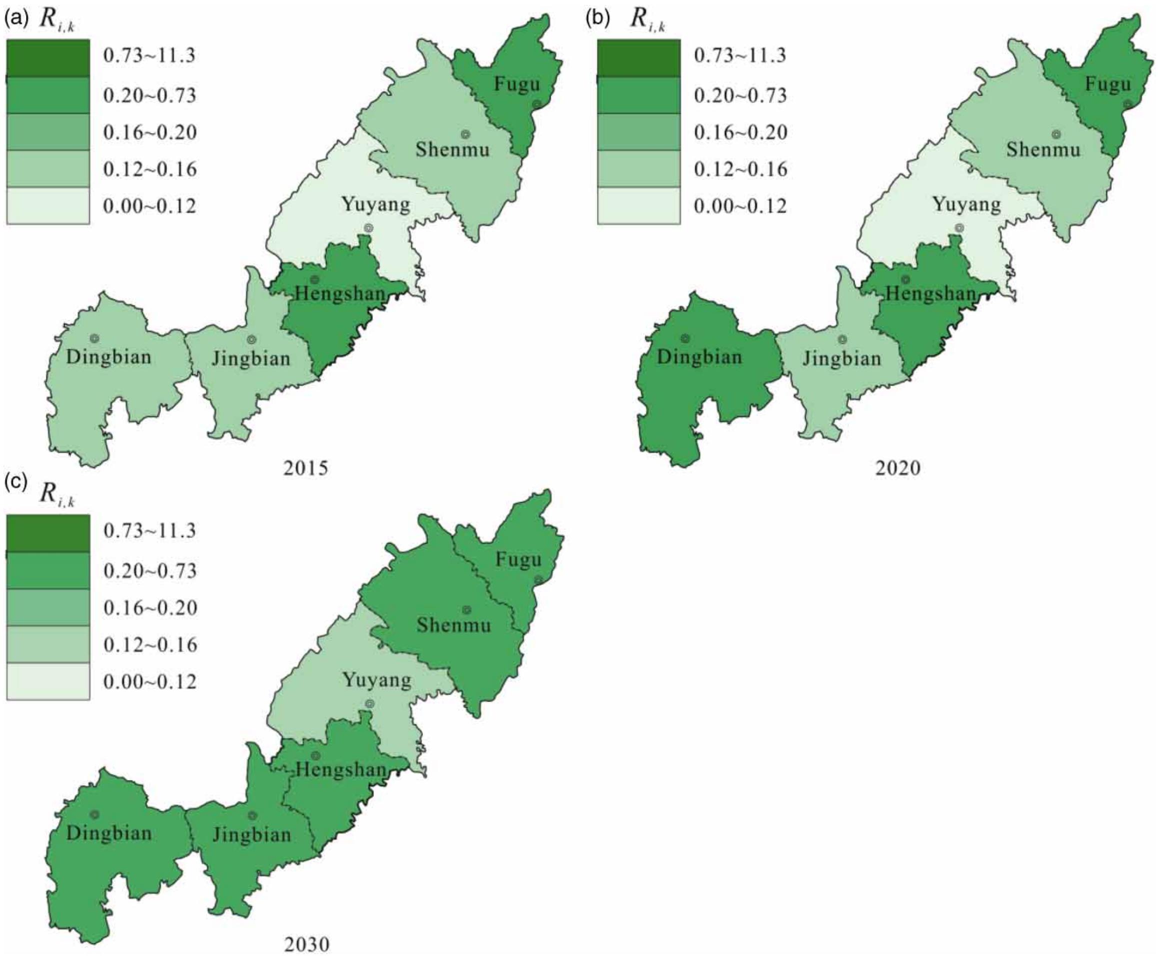

Figure 5 | The variations of matching patterns of land and water resources in ANS from 2015 (a), 2020 (b) and 2030 (c).

and cultivated land area are the prerequisites to ensure regional sustainable development. In this study, a water resources regulation-allocation coupling model involving two methodologies of 'regulation' and 'allocation' was constructed. Differentiated from the demand-oriented traditional agricultural water resource management strategy, the WRACM is water amount oriented. To cope with the increasing agricultural water consumption caused by the expansion of agricultural scale, the 'regulation' is to control the water consumption of agriculture and regulate the utilized scale with water resources as the main constraint; the 'allocation' is to optimize the water resources allocation among crops and arrange the crop planting system according to the water quota of different crops and the economic, social and ecological benefits brought by crops, to control the water resources among crops.

The proposed model was applied to the agro-pastoral ecotone of Northern Shaanxi Province in China, which is experiencing water scarcity problems and rapid expansion of sandy land agriculture. The main results are as follows:

(1) The intensity of water resources constraint differs by regions, while Yuyang county of ANS is the strongest one with the maximum exploited proportion of 8.11%, 18.36% and 91.28% respectively from 2015 to 2030. From a macroscopic view, the exploitable scale of ANS area is 16,443.4 ha (25.6%), 22,637.7 ha (36.9%) and 51,440 ha (93.7%) from 2015 to 2030.
(2) All the counties with adequate water resources are recommended for implementation of CS-3 to sustain crop diversity, otherwise when the developable ratio is insufficient to 100%, the recommended cropping scheme is

potato unitary cropping system with the least water consumption and the best comprehensive benefits.

(3) The proportion of remaining unused sandy land decreased year by year, which were 74.42%, 63.08% and 6.26% in 2015, 2020 and 2030 respectively. In terms of agricultural planting structure, potato cultivation still occupies an absolute advantage in the distribution of the cropping system, which is related to the higher yield and economic benefits of potatoes promoted by the natural geographical advantages in the ANS.

(4) The matching patterns of land and water resources in ANS show a weak attitude in the middle and high in the north and south. Overall, the average coefficient of the whole region raised gradually from 0.15 (in 'poor' degree) to 0.22 (in 'good' degree) from 2015 to 2030.

The proposed WRACM model provides a useful, quantitative tool for investigating the optimal water allocation strategy to improve the management of agricultural water sources. This method is expected to be a utilitarian approach and provides reference for water resources management in water-deficient areas.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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