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Construction and application of a refined index for measuring the regional matching characteristics between water and land resources

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ABSTRACT

In accordance with national policies, the Jiansanjiang Administration of Heilongjiang Province in China has assumed a heavy task of grain production in recent years. The spatial matching status of water and land resources is a prerequisite for grain production. To analyze the potential for grain production objectively, the matching characteristics of agricultural water resources and land resources in Jiansanjiang Administration were analyzed for this paper. The spatial distribution pattern of the water and land resources was analyzed, and the amount of broadly-defined agricultural water resources (BAWR) and cultivated area were introduced as the water resource and land resource quantity parameters, respectively. The Gini coefficient model for agricultural water and land resource matching and the model for measuring the matching index between the BAWR and land resources (MIBAWRLR) were then constructed to evaluate the degree of matching between agricultural water and land resources in Jiansanjiang Administration and 15 farms in the region. Based on the Cobb-Douglas all-factor production function, the input–output model of agricultural production was built, with the grain yield per hectare used as the explained variable and basic, technological, and natural factors as the explaining variables. The results are as follows: ① The results of the MIBAWRLR indicate that the matching situation between agricultural water resources and land resources in Jiansanjiang Administration has improved, which was consistent with the results of the Gini coefficient model. The matching situation on the farms of Jiansanjiang Administration worsened from south to north, and the spatial matching pattern was consistent with the spatial distribution of the proportion between blue water and green water at each farm, i.e., the matching situation on a farm with a high proportion of blue water was satisfactory. ② According to the input–output model of agricultural production, introducing the BAWR into the established models as the characteristic parameter of water resource quantity is scientific and reasonable.

1. Introduction

Water resources and land resources are the fundamental resources for regional economic development (Pan et al., 2010; Yang et al., 2013) and represent the core elements affecting agricultural production (Hou et al., 2012; Liu and Sun, 1999) as well as rigid constraints upon grain production (Yang et al., 2010; Yang et al., 2016). Shortages and inconsistencies between water and land resources are long-term and radically restrictive factors in the process of agriculture modernization (Brown and Halweil, 1998; Riquelme and Ramos, 2005). The degree of matching between water resources and land resources affects the comprehensive utilization rate and utilization efficiency of both water and land resources, which in turn affects regional agricultural production and sustainable development (Geng, 2014). Jiansanjiang Administration is the largest of 9 administrations in Heilongjiang Farms & Land Reclamation Administration. In recent years, within the background of the project *Consolidating and Improving Grain Production Total Amount to One Thousand Tons in Heilongjiang Province*, Jiansanjiang Administration has undertaken a heavy task of commodity grain production; the task involves a total grain yield of 6.58×10^6 t, which accounts for 1/3 of the production in Heilongjiang Farms & Land Reclamation Administration. Because of the impact of high-intensity

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agricultural exploitation, the quantity and quality of water and land resources in this region have changed significantly. The volume and reasonable utilization or not of water resources both directly impact the production efficiency and utilization pattern of land resources, while the degree of reclamation of land resources restricts the development and utilization of water resources. Therefore, conducting the matching research between water and land resources is of great practical significance for efficiently utilizing and optimal allocation of agricultural water and land resources, guaranteeing food security (Hou et al., 2012).

Thus far, matching between water resources and land resources has been studied by many scholars. Liu et al. (2006) analyzed the matching situation between water and land resources in the cities of Northeast China using the total water resources volume per hectare, which is the matching index between water and land resources, as the evaluation index and found that the matching situation in this region was inferior to that at the average national level. Li et al. (2016) evaluated the matching situation between agricultural water and land resources in Yanan and its 13 counties in Shanxi Province, China, by constructing a Lorenz curve and calculating a model of agricultural water and land resource matching. The results showed that the degree of matching of agricultural water and land resources in Yanan was poor and worse than that at the national average level for the same period. Obvious spatial differences were observed in the degree of matching, which worsened from south to north, in general. Huang et al. (2015) analyzed the matching situation between agricultural water and land resources in 21 cities in Sichuan Province, China by constructing a data envelopment analysis (DEA) model using the agricultural water resources and cultivated land resources as input indicators and the agricultural output value as the output indicator. The authors concluded that the model for measuring the water and land resource matching situation based on the DEA can strongly reflect the relationship between the degree of matching between regional water and land resources and agricultural output values. As shown above, the matching situation between water and land resources has been calculated using the following three methods: ① analyze the matching characteristics of water and land resources using the amount of water resources per hectare (i.e., the matching index of water and land resources) as the measurement indicator; ② study the equilibrium status of regional water and land resources by building up the Gini coefficient; and ③ investigate the matching characteristics of water and land resources based on the DEA model. Although the aforementioned methods are somewhat successful for measuring water and land resource matching, certain shortcomings have been observed: ① The Gini coefficient can represent only the overall degree of matching between water and land resources, and it reflects the relative relationship between each sub-region in the study area but cannot reveal the absolute matching situation. ② The influencing factors on the agricultural output value include water and land resources as well as the agricultural labor force and agricultural machinery power; thus, the DEA model provides unilateral and unscientific results when water and land resources are used only as the explanatory variables. ③ The matching index can display the relative spatiotemporal ratio between water resources and land resources and reveal the essence of water and land resource matching. The characteristic parameters of water resource quantity include the total water resource volume (Wu and Bao, 2003; Yang et al., 2016), the available water resource volume (Jiang et al., 2011; Li et al., 2016) and the irrigation water volume (Zheng et al., 2015).

In recent years, a paradigm shift has been observed in the field of global water resources and agricultural water, with the core element represented by the theory of blue water and green water (Li and Huang, 2010, 2015). Falkenmark (1995, 1997) considered that natural precipitation can be divided into two parts: blue water and green water, with blue water referring to precipitation stored by rivers, lakes, reservoirs and underground aquifers and green water referring to precipitation that is stored in unsaturated soil and available to plants. Therefore, broadly-defined agricultural water resources (BAWR) should also include blue water and green water. Agricultural blue water resources refer to water that is pumped from rivers, lakes or underground aquifers and used for agricultural irrigation, i.e., irrigation blue water (IBW), whereas agricultural green water resources represent the effective precipitation that can be absorbed by a crop and does not run off, i.e., effective precipitation green water (EPGW). Falkenmark and Rockström (2006) estimated that the amount of water used for global food production was approximately 6800 km^3/a, including IBW at 1800 km^3/a and EPGW at 5000 km^3/a. The research results of Liu et al. (2009) indicated that 80% of global food production is dependent on EPGW. Thus, EPGW contributes greatly to agricultural production. Therefore, the total water resource volume, the available water resource volume or the irrigation water volume are all unilaterally used as characteristic parameters of the water resource quantity of a region, and the matching situation should be considered from the perspective of the BAWR.

Based on the shortcomings of the aforementioned methods and the theory of blue water and green water, the objectives of this paper are as follows:

(1) construct the Gini coefficient model for agricultural water and soil resources based on the BAWR;
(2) construct the measuring model of the matching index between the BAWR and land resources (MIBAWRLR);
(3) analyze the spatiotemporal matching situation between regional agricultural water and land resources; and
(4) construct the input–output model of agricultural production based on the Cobb-Douglas production function and analyze the rationality and scientific soundness of the improved model.

2. Materials and methodology

2.1. Study area

The Jiansanjiang Administration, which is part of the confluence zone of the Heilongjiang River, the Ussuri River and the Songhua River, is in northeastern Heilongjiang Province, China. The study area is part of the Sanjiang Plain, and the geographic coordinates are between 46° 49′–48° 12′ N and 132° 31′–134° 32′ E. The terrain is low and flat, and most of the area of the region is a low plain or marsh (Liu et al., 2011; Yu et al., 2013). The main industrial sector in this region is agricultural production, and paddy fields are the main planting type. Fifteen farms are located in Jiansanjiang Administration, and the location and administrative divisions are shown in Fig. 1.

2.2. Data sources

Sixteen years (2001–2016) of data from each farm were organized based on the cultivated area, agricultural labor force, total power of agricultural machinery, applied fertilizer and pesticide amounts, and annual mean temperature from the Statistical Yearbook of the Jiansanjiang Administration. The monthly precipitation over sixteen years (2001–2016) was obtained from meteorological data provided by the Agricultural Bureau of Heilongjiang Farms & Land Reclamation Administration to calculate the EPGW. According to the annual reports on water conservancy (2001–2016) of Jiansanjiang Administration, the agricultural water consumption of each farm was determined to calculate the IBW, with irrigation water accounting for 90%–95% of agricultural water consumption (Li and Huang, 2010).

2.3. Theory of water and land resource matching

2.3.1. Gini coefficient model

The Gini coefficient proposed by Italian economist Gini was first applied to the study of income inequality (Gini, 1921). Because the spatial distribution of water resources shows diversity, the Gini