Evaluating the vulnerability of agricultural drought in Hetao Irrigation Area of Inner Mongolia Based on super efficiency DEA

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Abstract. Drought vulnerability has become a key point for agricultural sustainable development in such a changing context. In this study, Hetao Irrigation Area which is the major grain-producing area is selected as the research area, where frequent drought threatens food production. Firstly, super efficiency data envelopment analysis (SEDEA) model is used to evaluate the agricultural drought vulnerability of Hetao Irrigation Area from 1997 to 2016. And then the spatial and temporal differences of vulnerability are analyzed. Moran’s I Index is also adopted for further spatial autocorrelation analysis. The results show that the vulnerability decreases with the investment of agricultural science and technology, and the drought vulnerability in different irrigation fields are affected by the irrigation area coverage rate. The drought vulnerability is much higher in the east of Hetao Irrigation Area than that in the west due to the worse water supply in the east. And the vulnerability in Wuyan is the highest due to the largest cropping sown area, while Linhe stays the lower value due to the highest GDP.

1. Introduction
Drought is one of the most severe disasters that exerts bad effects on agricultural grain production[1]. Farmlands in China suffer from different degrees of drought every year[2]. From 1990 to 2005, the average area of farmland affected by drought reached 25.76*106 hm² every year, and the grain loss exceeded 26 million tons[3-4]. Claus Schwab, founder of the World Economic Forum, announced that, "Vulnerability is a reality facing the world. To achieve sustainable development, it is necessary to reduce development vulnerability first". Agricultural drought vulnerability refers to the degree of drought or the ability to withstand drought in agricultural areas[5]. It is a kind of uncertainty caused by drought environment, which may cause reduction or loss of agricultural grain production. As an agricultural country, the vulnerability of agricultural drought will affect the survival of human beings.

Many scholars consider evaluating the agricultural drought from the perspective of vulnerability. Generally speaking, the commonly method can be divided into two categories. One is the index synthesis: such as entropy method[6], analytic hierarchy process[5], grey relational method[7]. A comprehensive index is generated to evaluate the relative degree of vulnerability of the unit. Another is to construct a function method: based on understanding vulnerability, and then the model can be established. However, different scholars share different understandings of the vulnerability of agricultural drought. In addition, there exits obvious subjectivity when weighing the indexes and constructing the vulnerability functions. Thus evaluation results vary a lot, with large differences and low credibility.
Data Envelopment Analysis (DEA) is proposed to evaluate vulnerability of disasters which is a linear programming technique accommodating both multiple inputs and multiple outputs. Super Efficiency Data Envelopment Analysis (SEDEA) is an improvement of traditional DEA model, which is widely used to solve the problem that the high-low ranking cannot be directly compared because of the efficiency of multiple decision-making units. Fuhua Sun et al.[8] used the SEDEA model and Malmquist index to measure the 18 provinces’ water resources utilization efficiency in 2011-2015 years; Guangyao Deng et al.[9] used SBM-DEA model to evaluate water resource utilization efficiency in 31 provinces from 2004-2013; Huan Pei et al.[10] used DEA to build a drought vulnerability evaluation model, and analyzed the spatial and temporal characteristics of agricultural drought vulnerability in recent 40 years. Therefore, based on the application of SEDEA model, an evaluation model of agricultural drought vulnerability in Hetao Irrigation area is proposed in this paper.

2. Study area
Hetao Irrigation Area is located in the north of the Yellow River in Inner Mongolia plateau. The Yellow River to the east carries a large amount of silt, after years of erosion, formed a ribbon plain. With the development of large-scale water conservancy projects, the Hetao Irrigation Area is gradually formed. It contains seven counties (see in Figure 1). Hetao Irrigation Area is generally divided into five irrigation fields, they are Yongji, Yichang, Ulanbuh, Urad, Jiefangzha. Each irrigation field is responsible for agricultural irrigation of several counties around. It is an important commodity grain and oil production base in China. This area suffers high temperature and drought in summer. Frequent drought brings a decrease in food production and furthermore restrict the agricultural sustainable development.

3. Research methods and data

3.1. Research methods

3.1.1. SEDEA
Compared with the traditional DEA model, SEDEA mainly solves the problem that the high-low ranking cannot be directly compared due to the efficiency of multiple decision-making units. Suppose there are n decision-making units DMU (j = 1, 2, ..., n). Each DMU has m inputs and s outputs, and the input vector is $X_j = (x_{1j}, x_{2j}, ..., x_{mj})^T$, the output vector is $Y_j = (y_{1j}, y_{2j}, ..., y_{sj})^T$. SEDEA model is as follows:

$$\begin{align*}
\min \{ \theta - \varepsilon (e^T S^- + e^T S^+) \} \\
\text{s.t.} & \sum_{j=1,j \neq 0}^n X_j \lambda_j + S^- = \theta X_0 \\
& \sum_{j=1,j \neq 0}^n Y_j \lambda_j - S^+ = Y_0 \\
& \lambda_j \geq 0, X_j \geq 0, Y_j \geq 0, j = 1, 2, \ldots, n \\
& e^T = (1, 1, \ldots, 1) \in E_m, \quad e^T = (1, 1, \ldots, 1) \in E_n
\end{align*}$$

(1)
In which: θ is the planning objective value, and λ_1 is the planning decision variable. The super-efficiency value of effective DMU will generally be greater than 1. It indicates that the higher the super-efficiency value is, the higher the vulnerability level of regional agricultural drought is. In addition, the fluctuation of drought vulnerability in different regions can be measured by the Coefficient of Variation. The higher the inter-annual stability of drought vulnerability is, the smaller the Coefficient of Variation will be. As follows:

\[ CV = \frac{SD}{\bar{x}} \]  

(2)

In which: SD represents the standard deviation of vulnerability, and \( \bar{x} \) is the average of vulnerability.

3.1.2. Moran’s I Index

Moran’s I index is used for global clustering inspection of a more mature way. It tests whether there is similarity, difference or independence between adjacent units in the whole area. Judge this phenomenon or attribute value aggregation behaviour does exist in space. Moran index is as follows:

\[ I = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} (x_i - \bar{x})(x_j - \bar{x})}{S^2 \sum_{i=1}^{n} x_i} \]  

\[ S^2 = \sum_{i=1}^{n} (x_i - \bar{x})/(n-1) \]  

\[ \bar{x} = \frac{\sum_{i=1}^{n} x_i}{n-1} \]  

(3)

Where \( n \) is the number of research units; \( x_i \) and \( x_j \) are vulnerability values of unit \( i \) and unit \( j \); \( \bar{x} \) is the average vulnerability of all units; \( S^2 \) is the variance of vulnerability; \( W_{ij} \) is the spatial weight matrix of element \( i \) and element \( j \). The value is generally between -1 and 1. The value closing to 1 indicates that there is a spatial pattern of similar attribute clustering in regional units while it closing to -1 indicates that there is a spatial division of different attributes clustering in regional units.

3.2. Index Selection

The total population, total planting area, and GDP are selected as input indicators, crop drought affected area and crop drought area are selected as output indicators (see in Table 1). Among these indexes, the total population and total planting area reflect the exposure of disaster victims; vulnerability grows with the agricultural system increase exposure on the whole. GDP reflects the ability of agricultural drought recovery. Vulnerability decreases as GDP increases and drought resilience increases. Crop drought affected area and crop drought area comprehensively reflect agricultural drought losses. The SEDEA model is used to evaluate the vulnerability of droughts in agricultural regions.

| Table 1. Agricultural Drought Vulnerability Index System in Hetao Irrigation Area |
|---------------------------------|---------------------------------|-------------------|
| **Index**                       | **Index description**           | **Unit**          |
| Input Index                     | The total population            | Reflecting the exposure of disaster-bearing body |
| Total planting area             | Total planting area             | Ten thousand people |
| GDP                             | Reflecting the ability of agricultural drought recovery | Million hectares |
| Output Index                    | Crop drought affected area      | Reflecting agricultural drought losses |
| Crop drought area               |                                | Million hectares  |

3.3. Data

Data used in this study are from Inner Mongolia Statistical Yearbook and China Regional Economic Statistical Yearbook, compiled by China Statistical Publishing House covering the period 1998-2017.

4. Results

4.1. Vulnerability evaluation results

The average vulnerability values of the study area during 1997-2016 are showed in Figure 2. The average vulnerability of Wu county is the highest among these seven counties, followed by Urad Middle Banner, both are in the Yichang Irrigation Field. Urad Front Banner is ranking 3 which belong to Urad.
Irrigation Field. Dengkou and Linhe, ranking 4 and 5 respectively. They belong to Ulanbuh Irrigation Field and Yongji Irrigation Field. The lowest vulnerability is found in Jiefangzha Irrigation Field covering the Urad Rear Banner and Hanggin Rear Banner.

Figure 2. Spatial distribution of average vulnerability in study area

4.2. Temporal and spatial analysis

Figure 3 shows spatial and temporal distribution of Hetao Irrigation Area within 20 years. Among them, the vulnerability of Wuyuan is the highest before 2007, and then the Urad Middle Banner goes beyond it. The vulnerability of Urad Rear Banner and Hanggin Rear Banner covered by Jiefangzha Irrigation Field are stay the lower two in all years. In addition, the vulnerability of Linhe is also low which is the city centre of Bayan Nur.

Figure 4 shows the general change trends of vulnerability in different irrigation fields are similar in different 5-year periods. It falls down slowly from the 9th Five-year Plan period to 11th Five-year Plan period, while it presents a sharp downward trend after that. It is worthwhile to note that the vulnerability changes show a slight recovery trend, from the 12th Five-year Plan to the early 13th Five-year Plan. Figure 5 shows the general change trends of vulnerability in different periods, including the 10th Five-year Plan, 11th Five-year Plan, 12th Five-year Plan. In these three periods, besides Hanggin Rear Banner and Wuyuan, there is a small rise trend and then a sharp fall in other five counties. However, the overall trend is downward.

Figure 3. Spatial and temporal distribution of Hetao Irrigation Area within 20 years
Figure 4. The trend of average vulnerability during different five-year plan period.

Moran’s I Index is 0.517535 (see in Table 2), indicating that the vulnerability level of agricultural drought in Hetao Irrigation Area has a positive spatial correlation. P value is less than 0.05, which indicates that the null hypothesis of random distribution is rejected, and the vulnerability value of each county is not randomly distributed. The Z value score is greater than 1.96, indicating that the vulnerability level of agricultural drought disaster in 7 counties has obvious clustering characteristics. The results show that the distribution of agricultural drought vulnerability in Hetao Irrigation Area show obvious regional characteristics. Areas of high vulnerability are distributed together. It's also obvious that the vulnerability value in east region is generally higher than that in west region from Figure 2.

Table 2. Global Moran’s I Index of agricultural drought vulnerability assessment value in Hetao Irrigated Area

| Moran’s I Index | Expectations index | Variance | Z score | P value |
|-----------------|--------------------|----------|---------|---------|
| 0.517535        | -0.166667          | 0.100075 | 2.162947| 0.030545|

5. Discussion and conclusion

5.1. Discussion

In this study, the agricultural drought vulnerability of Hetao Irrigation Area is evaluated from 1997 to 2016. This is the first study to evaluate the agricultural drought vulnerability from the perspective of county level. The vulnerability is obtained in smaller scales than previous study. For example, Huan Pei et al.[10] used DEA model to evaluate agricultural drought vulnerability all around China. And there are other studies also assessed vulnerability at the national or provincial level.

From the temporal perspective, the vulnerability values present the downward trend in the past 20 years. It falls down slowly from the 9th Five-year Plan period to 11th Five-year Plan period, while it presents a sharp downward trend after that. It is mainly due to the significant investment in agriculture including constructions of water saving irrigation projects in 11th Five-year Plan period and the persistent investment in 12th Five-year Plan period. It is worthwhile to note that the vulnerability changes show a slight inclining trend in the late 12th Five-year Plan and early 13th Five-year Plan. According to the local weather records, there are serve drought events in Inner Mongolia from 2013, 2014 and 2016.

The drought vulnerability in different irrigation fields are affected by the irrigation area coverage rate. Drought vulnerability values in Yichang Irrigation Field and Urad Irrigation Field are much higher than that in Jiefangzha Irrigation Field and Yongji irrigation Field. Detecting the irrigation coverage rate which is calculated by dividing irrigation area by total area, the irrigation coverage rate
of Yongji is over 70% and that of Jiefangzha is also over 65%. However, the irrigation coverage rate of Yichang Irrigation Field and Urad Irrigation Field is below 60%. In addition, the vulnerability is much higher in the east of Hetao Irrigation Area than that in the west. And it shows agglomeration in space distribution. From the perspective of the underground water quality of each irrigation field, Ulanbuh, Jiefangzha and Yongji in west region are in good water quality, with scattered distribution of salt water and brackish water appearing. However, the water quality of Yichang Irrigation Field and Urad Irrigation Field in east region is poor, and the distribution of salt water and brackish water is very wide.

5.2. Conclusion
In this study, agricultural drought vulnerability of Hetao Irrigation Area is evaluated from 1997 to 2016 using SEDEA model. And then the spatial and temporal differences of vulnerability are analysed. The evaluation results show that the vulnerability decreases with the investment of agricultural science and technology. The overall trend of average vulnerability during 20 years is declining. Specifically, it declines slowly from the 9th to 11th Five-year Plan period, and then declines sharply during 12th Five-year Plan period which is mainly due to the sustained and stable investment in agriculture. The drought vulnerability in different irrigation fields are affected by the irrigation area coverage rate. Drought vulnerability values in Yichang Irrigation Field and Urad Irrigation Field where the irrigation area coverage rate is below 60%, are much higher than that in Jiefangzha Irrigation Field and Yongji Irrigation Field where the irrigation area coverage rate is over 60%. The drought vulnerability in different counties vary greatly depending on geographical conditions and social environments. The drought vulnerability is much higher in the east of Hetao Irrigation Area than that in the west due to the worse water supply in the east. And the vulnerability in Wuyan is the highest due to the largest cropping sown area, while Linhe stays the lower value due to the highest GDP.

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