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Risk Assessment of Cold Damage to Maize Based on GIS and a Statistical Model

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Abstract: Cold damage to maize is the primary meteorological disaster in northwest China. In order to establish a comprehensive risk assessment model for cold damage to maize, in this study, risk models and indices were developed from average daily temperature and maize yield and acreage data in 1991-2012. Three northwest provinces were used to calculate the temperature sum during the growth period, temperature departure over the years and relative meteorological yield in order to obtain the climate risk index, risk sensitivity index and damage assessment index. Using the geographic information system (GIS) and cold damage risk indices obtained from the statistical assessment model, the studied area was divided into four risk regions: low, medium, medium-high and high. Northeast and southwest Gansu were grouped to the high-risk region; west Shaanxi and north NHAR were grouped into to the low-risk region; all other areas fell into medium and medium-high risk regions. Our results can help growers avoid cold damage to maize using local climate data and optimize the structure and layout of maize planting. It is of significance in guiding the agricultural production in the three northwest provinces in China and also can serve as a reference in modeling risk assessment in other regions.

Keywords: Maize, climate, cold damage, risk assessment, geographic information system (GIS).

1. INTRODUCTION

Shaanxi, Gansu and the Ningxia Hui Autonomous Region (NHAR) are three major provinces in northwest China. Topographically, they include the Qinba Mountains in south Shannxi, the Guanzhong Plain, the Loess Plateau in north Shannxi, the Hexi Corridor in Gansu and Qilian Mountain in NHAR. Digital elevation model (DEM) data show that altitudes of this undulating terrain vary from over 3,000 meters to below 1,000 meters above sea level. Hence, temperature changes are relatively dramatic [1] , and extreme weather may easily occur. Damage due to cold weather is of notable regionality [2]. North Shannxi, part of Gansu, and the majority of NHAR are important maize growing areas of China. According to data published on the website of the Farming Management Division of the Ministry of Agriculture of the People's Republic of China, the present total maize acreage of these three provinces is approximately 2 million hectare (ha), with a yield of 4500-7500 kg per ha; i.e., in a normal year, the total maize yield is approximately 10 million tons. If moderate cold damage occurs, the yield can be reduced by 5-15%, which is approximately 1 million tons of maize, equivalent in value to nearly 17 million dollar. If there is severe cold damage during the growth period, the yield will be reduced by 15-25% which is approximately 2 million tons of maize, equivalent in value to nearly 35 million dollar.

Due to the impact of global warming, in recent years, temperature conditions have improved in general, and the number of years with severe cold damage has been reduced. However, as extreme weather events tend to frequently occur, the amplitudes of temperature fluctuations in different regions increase. In the future, there will still be years of low or relatively low temperature. In addition, crop rotation, intercropping and other cultivation methods are being practiced in many places, and efforts are being made to cultivate late maturing varieties..Thus, once cold damage occurs, it will cause even more severe agricultural economic losses than ever before [3]. Therefore, it is necessary to study the risk of cold damage to maize.

Prior studies on cold damage to maize and rice in China have mainly focused in the northeast region. The studies on cold damage in the northwest of China are limited to the following reports. Li and Wang [4] classified Gansu and NHAR as provinces with serious freeze damage. Li *et al.* [5]

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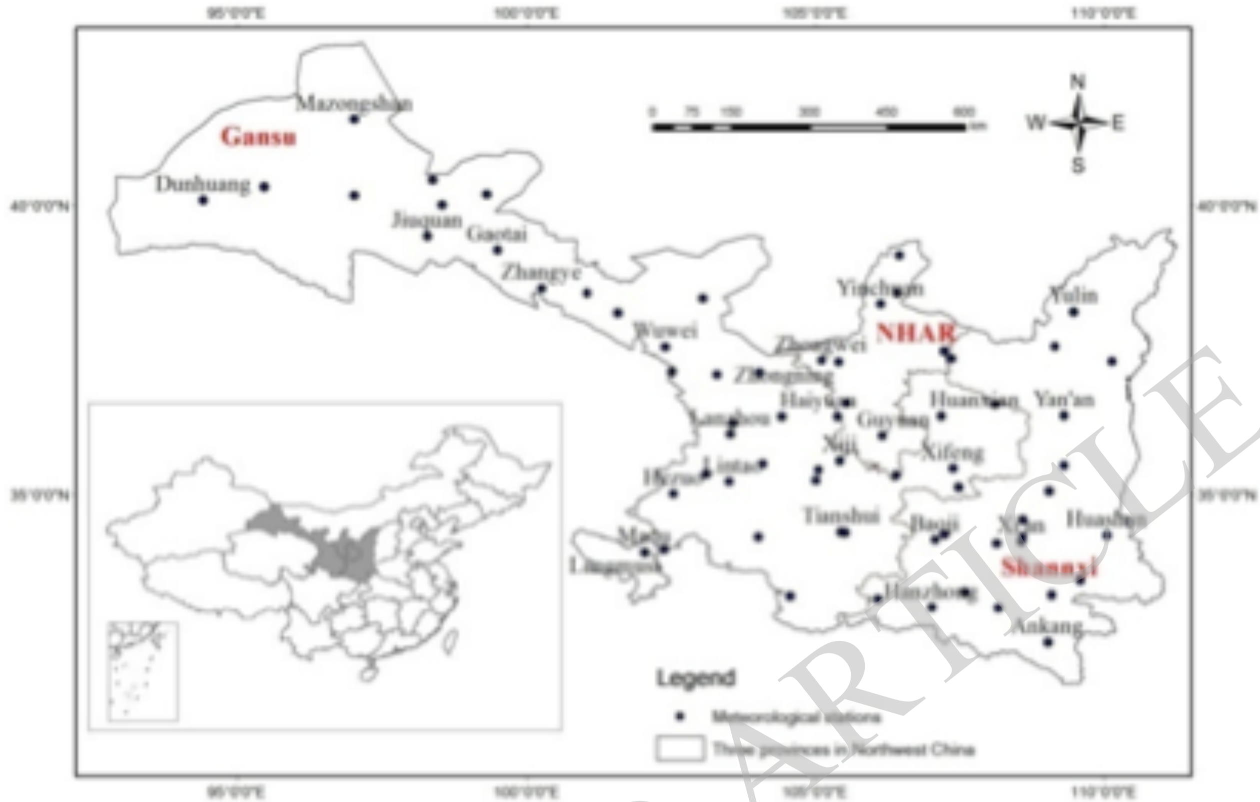

Fig. (1). Location of the studied area and spatial distribution of meteorological stations.

reported that the type of weather that causes cold damage was relatively common in Gansu; Li *et al.* [6] investigated cold damage to rice in NHAR. Liu *et al.* [7] designed a risk index of cold damage to apples in the Shannxi region according to the flowering time of apples. However, there has been no report on cold damage to maize in northwest China, its risk assessment or assessment indices.

In our investigation, meteorological data and maize yields and acreage in three northwest provinces (Gansu, NHAR, and Shannxi) were used to explore cold damage to maize using a mathematical model based on the temperature sum needed for crop growth. In order to effectively improve the intuitiveness of the risk assessment results, in addition, GIS technology was used in classifying the degree of risk. The goal of our study is to provide a theoretical basis for scientific measures of cold damage and prediction models to prevent cold damage. The objectives of this paper are to (1) build a model of a comprehensive risk assessment for cold damage to maize and (2) classify the degree of risk.

2. MATERIALS AND METHODS

The three northwest provinces are located at 31°42’-42°57’N, 92°13’-111°15’E, expanding about 2350 km from west to east and about 1000 km from north to south (Fig. **1**). They include Gansu Province, the NHAR and Shannxi Province, with a total area of about 725,500 km², approximately 7% of the total area of China. Average daily temperature data collected from 73 meteorological stations (28 in Shannxi, 35 in Gansu and 10 in NHAR) from 1951 to 2012 were used. Data on maize growth and development from 1991 to 2012 were provided by the China Meteorological Data Sharing Network (http://cdc.cma.-gov.cn/). Data on the total yield of maize, yield per unit area and total acreage were obtained from provincial rural statistical yearbooks.

Identification of cold damage to maize in the three northwest provinces was based on the meteorological industry standard "level of cold damage to rice and maize"(QX/T101-2009which is a National Industry Standards) Table **1** lists indicators of level of cold damage to maize during growth periods; T (°C) is the average of sum temperature from May to September over all the years examined and ΔT (°C) is the temperature departure of the average monthly temperature of May-September of a particular year from that of the entire years. For data collected in each meteorological station, average daily temperatures were used to calculate the average monthly temperature of each year. Then, based on the indicator table (Table **1**), the years, frequency and sites at which general and severe cold damage occurred during growth period were determined.

Table 1. Indicators of maize yield reduction due to cold damage.

Degree of Damage	T≤80	80<T≤85	85<T≤90	90<T≤95	95<T≤100	100<T≤105	Yield Reduction Rate
General cold damage	-1.7<ΔT≤-1.1	-2.4<ΔT≤-1.4	-3.1<ΔT≤-1.7	-3.7<ΔT≤-2.0	-4.1<ΔT≤-2.2	-4.1<ΔT≤-2.2	5-15%
Severe cold damage	ΔT ≤-1.7	ΔT ≤-2.4	ΔT ≤-3.1	ΔT ≤-3.7	ΔT ≤-4.1	ΔT ≤-4.4	>15%

Multiple methods are available for simulating trend yield [8]. In the present study, the linearly weighted moving average method was used because with this method, no sample data are lost, and the stimulation result is relatively good [9, 10]; the step size was set to 11, and meteorological yields were obtained.

2.1. Comprehensive Indicators of Cold Damage Assessment

A. Climate Risk Index

Climate risk is a natural attribute of agricultural disasters. In this study, changes in the temperature during crop growth and the frequency of low temperature were analyzed to obtain the climate risk index. The amount of total heat can be used to indicate whether cold damages occurs in a particular year in a certain region. The inter-annual stability of temperatures also directly relates to the risk of cold damage to crops. Thus, temperature data from 1951-2012 were used to calculate the coefficient of variation (CV) of T in meteorological stations in Gansu, NHAR and Shannxi provinces.

$$CV = \frac{1}{\overline{T}} \times \sqrt{\frac{\sum_{i=1}^{n}(T_i - \overline{T})^2}{n-1}} \quad (1)$$

where CV is the coefficient of variation, $\overline{T}$ is the mean of $T_{5\text{-}9}$ over the period of 1951-2012, T_i is the value of a certain year in a certain region, and n is the total number of years.

B. Probability of Cold Damage

Compared to the frequency of cold damage, when the sample size is large enough, the probability of cold damage is not subject to change as the number of years increases, and thus is of higher objectivity and stability. Before calculating the probability of cold damage, a skewness-kurtosis test on climate samples determines if the data fits a normal distribution. If the distribution is skewed it is transformed into a normal distribution [11].

Skewness: $$C_s = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^3}{[\frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^2]^{\frac{3}{2}}} \quad (2)$$

Kurtosis: $$C_e = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^4}{[\frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^2]^{2}} \quad (3)$$

$\bar{x}$ is the mean of $T_{5\text{-}9}$ over the period of 1951-2012, x_i is the $T_{5\text{-}9}$ value of a certain year in a certain region, and n is the total number of years.

Based on meteorological data collected in Shannxi, Gansu and NHAR from 1951-2012, the skewness-kurtosis values over 50 years were calculated. By comparing the results with the values on the critical value table [12], it was concluded that the data all fit a normal distribution. Thus, the risk probability at corresponding levels of cold damage can be obtained based on the assumption of a normal distribution. The probability density function is as follows:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(x-\mu)^2}{2\sigma^2}} \quad (4)$$

where x is the value of ΔT sequence, μ is the mathematical expectation and can be replaced by the mean in a large sample sequence (sample size ≥ 30), and σ is the standard deviation. Integration of the probability density function was performed to obtain climate risk probability at different cold damage indicators:

$$F_1 = \int_{\Delta T_2}^{\Delta T_1} f(x)dx \quad (5)$$

$$F_2 = \int_{-\infty}^{\Delta T_2} f(x)dx \quad (6)$$

where F_1 and F_2 are the probabilities of moderate and severe cold damage, respectively, and ΔT_1 and ΔT_2 denote ΔT in moderate and severe cold damage, respectively (see Table **1** for reference).

C. Climate Risk Index of Cold Damage

The climate risk index of cold damage is a comprehensive index combining the intensity and frequency of cold damage [13] and can objectively reflect the degree of the risk of cold damage. The years with cold damage were divided into two groups: the moderate and severe cold damage groups. In each group, the frequency of the corresponding level of cold damage occurring over the years D_i and the median value H_i were calculated. The climate risk index k was calculated according to the following formula:

$$k = \sum_{i=1}^{2} \frac{D_i}{n} \times H_i \quad (7)$$

where D_i is the number of years in which the corresponding level of cold damage occurred (Table **1**), H_i is the mean of the corresponding maximum and minimum values and n is the total number of years.

D. Risk Sensitivity Index

Risk sensitivity index is determined by the production layout of the crop and includes physical exposure index (S_1) and disaster resilience index (S_2). Physical exposure refers to the ratio of crop acreage to the geographical area of the studied area, i.e., larger planting area and higher proportion of the total land area will increase the sensitivity to risk correspondingly. In addition, planting density also affects physical exposure. S_1 is calculated using the following equation:

$$S_1 = \frac{S_i}{C_i} \tag{8}$$

where S_i is regional maize acreage in units of square hectometers (hm²), C_i is the land area of this region in hm², and i stands for different areas.

The disaster resilience index (DRI) mainly depends on three factors: genetics, productivity and yield. The DRI is positively correlated with the resistance of the crop itself, which is determined by the genetic characteristics. For example, resistant varieties have high resistance. The DRI is also positively correlated with the level of agricultural productivity; for example, taking agricultural cultivation measures such as optimization of sowing time and transplanting time, ground cover and artificial irrigation and using special equipments can improve disaster resilience. The DRI is positively correlated with agricultural yield [14]. Currently, the DRI is often defined by yield [15]. In this study, relative maize yield per unit area in each region was used as the DRI.

$$S_2 = \frac{P_i}{P} \tag{9}$$

where P_i is the maize yield per unit area in one region in kg and P is the average maize yield per unit area of an entire province in kg.

Prior methods for assessment on agricultural loss due to meteorological risk mainly involve the establishment of risk indicators of disaster intensity and the loss risk assessment model [16]. In this study, the loss assessment index of cold damage was obtained from 1) the mean yield reduction rate, 2) the CV of yield reduction rates in years when cold damage occurred, 3) the probability of yield reduction rates in different ranges, and 4) the yield reduction risk index and other indicators for comprehensive assessment of the maize yield loss.

1) Average Yield Reduction Rate

The difference between trend yield and the actual yield per unit area in percentage is called "yield reduction rate" (i.e., relative meteorological yield). The relative meteorological yield is a relative value, indicating the amplitude of the deviation of actual yield from trend yield [17]. The normalized relative yield data can be treated as normal data, and the mean and variance were calculated as characteristic parameters. These data were combined with relative yield data that passed the normality test, and risk assessment was performed based on the assumption that all relative yield data fit a normal distribution.

Average yield reduction rate can reflect the level of average yield reduction caused by cold damage in a certain region. As shown in Table **1**, years in which the yield reduction rate was greater than 5% were considered as years of disaster. The average yield reduction rates in years of disaster in different counties (cities) of the studied area were calculated using Eqns. 10 and 11.

$$Y_1 = \sum_{0.15 > y_i > 0.05} \frac{y_i}{k_1} \tag{10}$$

$$Y_2 = \sum_{y_i \geq 0.15} \frac{y_i}{k_2} \tag{11}$$

where Y_1 and Y_2 are the average yield reduction rate in moderate and severe yield reduction years, respectively, y_i is the yield reduction rate sequence, k_1 and k_2 are the total number of samples in years of moderate and severe cold damage, respectively.

2) CV of Yield Reduction Rate

According to Eqn. 1, the CV of the maize yield reduction rate in years of disaster, CV_z, was calculated to describe the amplitude of fluctuation of maize yield loss in years affected by disaster. High CV_z indicates that the region experiences a relatively large number of years of moderate and severe yield reduction, suggesting that the growth environment is relatively fragile and subject to relatively high risk of yield reduction due to external conditions.

3) Risk Probability of Yield Reduction

Fluctuation in crop yield is very clear due to the influence of climate and temperature. Because the constructed yield reduction rate sequence fits a normal distribution, risk probability of yield reduction can be calculated. The risk probabilities of maize yield reduction in different counties (cities) of the three northwest provinces were calculated using Eqns. 12 and 13:

$$P_1 = \int_{0.05}^{0.15} f(x)dx \tag{12}$$

$$P_2 = \int_{0.15}^{\infty} f(x)dx \tag{13}$$

where P_1 and P_2 are the risk probability of moderate and severe yield reduction, respectively, x is time sequence of yield reduction rate that passed the normality test or had been subject to normalization.

4) Loss risk Index of Cold Damage

Like climate risk index of cold damage, loss risk index is also a comprehensive index reflecting the amplitude and frequency of yield reduction and can objectively reflect the

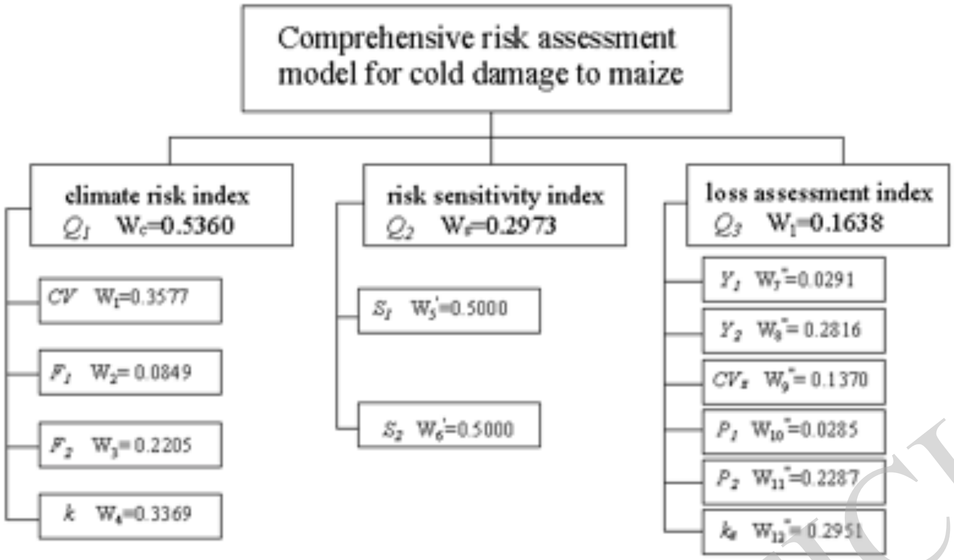

Fig. (2). Comprehensive risk assessment model for cold damage to maize and weight coefficients. CV is the coefficient of variation. F1 and F2 are the probability of moderate and severe cold damage, respectively. k is risk index. S1 and S2 are physical exposure and disaster resilience indices, respectively. Y1 and Y2 are average yield reduction rates in moderate and severe yield reduction years, respectively. CVz is the CV of the maize yield reduction rate in years of disaster. P1 and P2 are the risk probability of moderate and severe yield reduction. kz is the loss risk index of cold damage.

degree of the loss risk of cold damage. According to Eqn. 7, the product of frequency of moderate yield reduction and group median value was added to the product of frequency of severe yield reduction and group median value to obtain the loss risk index of cold damage k_z.

2.2. Comprehensive Risk Assessment Model for Cold Damage

To comprehensively reflect the risk of cold damage, all indices were combined with corresponding weight coefficients. After range standardization, the values of all indices were between 0-1, and the influence of different range of magnitude of indices was eliminated. Range standardization was performed using Eqn. 14:

$$x_i = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \tag{14}$$

where x and x_i are index values before and after standardization, respectively; x_{max} and x_{min} are the maximum and minimum value of the same index in all regions in the studied area, respectively.

Weighted composite indices were calculated using Eqns. 15- 17, including climate risk index (Q_1), risk sensitivity index (Q_2) and loss assessment index (Q_3), where W, W' and W'' are corresponding weight coefficients (Fig. **2**). These indices were then combined to establish the comprehensive assessment model using Eqn. 18 where W_c is the weight coefficient of climate risk index Q_1, W_s is the weight coefficient of risk sensitivity index Q_2 and W_l is the weight coefficient of loss assessment index Q_3.

$$Q_1 = W_1 \times CV + W_2 \times F_1 + W_3 \times F_2 + W_4 \times k \tag{15}$$

$$Q_2 = W_5' \times S_1 + W_6' \times S_2 \tag{16}$$

$$Q_3 = W_7'' \times Y_1 + W_8'' \times Y_2 + W_9'' \times CV_z + W_{10}'' \times P_1 + W_{11}'' \times P_2 + W_{12}'' \times k_z \tag{17}$$

The comprehensive risk model is:

$$R = W_c \times Q_1 + W_s \times Q_2 + W_l \times Q_3 \tag{18}$$

The AHP was used to determine index weight. The importance of three indices is empirically rated as climate risk index > risk sensitive index > loss assessment index, and their weights W_c, W_s and W_l were determined as shown in Fig. (**2**). Taking into account that the physical exposure (S_1) can be reflected with regional disaster resilience index (S_2), the weights (W_5 *and* W_6) for these two indices were given the same. Determination of all weight coefficients was completed with the AHP analysis software yaahp V6.0 (http://www.yaahp.com/). The consistency test statistic was 0.0331, less than 0.1, i.e., the result passed the consistency test.

3. RESULTS

Regionalization

Using the spatial and temporal variation of temperatures, the amplitudes of risk of cold damage to maize during the growth period in different regions was analyzed. ArcGIS10 was used to plot the calculated CVs into elements on a map. As the results shown, the largest portion of the CVs were

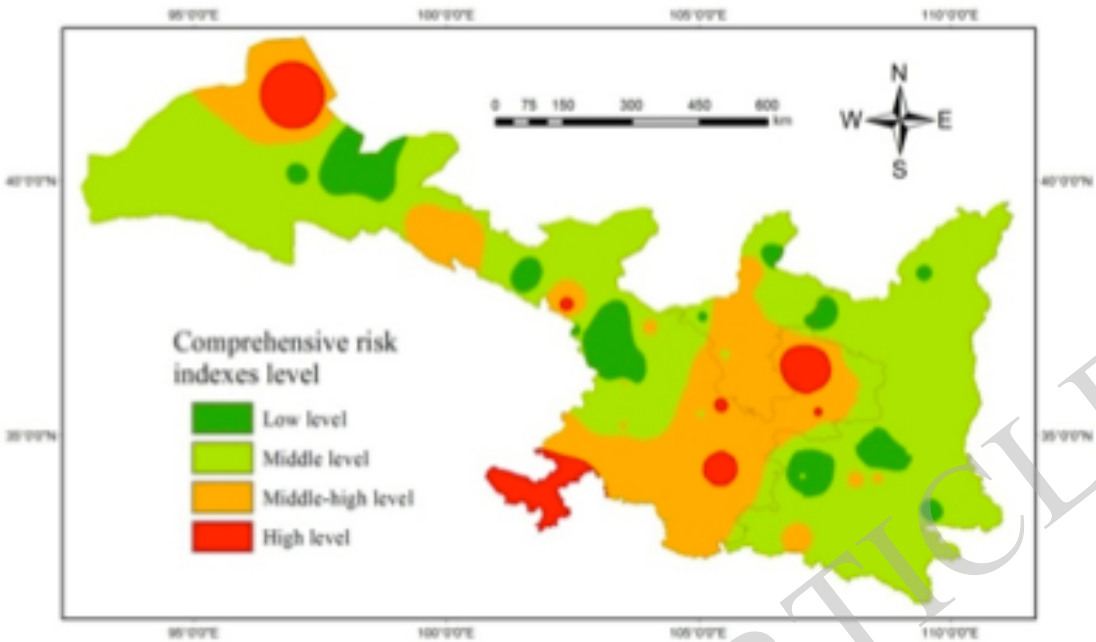

Fig. (3). Distribution of comprehensive risk index of cold damage to maize in the three northwest provinces.

above 0.04, followed by those between 0.03 and 0.04; those 0.03 below accounted for the lowest proportion of all CVs. Regarding spatial distribution, in northwest Gansu there was ample heat, and temperature was relatively stable, whereas in southwest Gansu, temperature variation was relatively large. Results show that CVs in Maqu and Langmusi reached a maximum, and variation in the Hexi Corridor in Gansu was also relatively large; heat variation in central and west Shannxi was relatively small and heat variation in NHAR was medium. In addition, the CV of moderate cold damage index and that of severe cold damage index were also calculated; a higher value indicated more severe disaster and higher risk (data not shown).

According to the industry standard of cold damage to maize (Table **1**), the calculated risk probabilities of cold damage of different regions in the three northwest provinces were used for zoning analysis. As illustrated in Fig. (**3**), sites with high risk probability of cold damage such as Zhangye (18%) and Wuwei (17%) were also regions of relatively high CV. It was found that the risk index of Xifeng in Gansu was the highest, reaching 1.49. The risk indices of Yan'an, Wuwei and Zhangye were all at about 1.4. At all other sites except Linxia, the risk indices were between 0.86-1.17; at Linxia, the risk index was 0.05, almost negligible.

The comprehensive risk index *R* was calculated using Eqn. 18 and the weight coefficients shown in Fig. (**2**). With the natural break classification method, the studied area was divided into four risk areas: low, medium, medium-high and high (Fig. **3**). The regions of highest risk to cold damage included Mazongshan, Maqu, Langmusi and Huanxian. The regions of lowest risk included Xi'an, Lanzhou, and Yinchuan *et al.*

4. DISCUSSIONS AND CONCLUSION

According to the studied area data in 1951-2012 of meteorological disasters information, choose 1962, 1967, 1968, 1977, 1984, 1989, 1993, 1996, 2001, 2004 and 2006 as typical cold damage years, perform the statistics over the average yield reduction rate, and analysis of the correlation between average yield reduction rate and the Chilling average risk index during typical years in the counties (cities), which is to verify the feasibility and applicability of the comprehensive risk assessment model for cold damage.

By analyzing the regression relationship between the comprehensive risk index and maize average yield reduction rate in typical chilling years, we can know that they meet the 0.05 level of significance related. So it is reliable to the comprehensive risk assessment model for cold damage which is established by climate risk index (Q_1), risk sensitivity index (Q_2) and loss assessment index (Q_3). We can infer from the maize yield reduction degree affected by chilling damage.

Three provinces in northwest China were selected for a study on risk of cold damage to maize. The risk assessment index of cold damage and a crop damage assessment system were established using a combination of meteorological data. The weight of each index from the Comprehensive Weight Method was determined based on AHP method and overcame the limitations of deflection caused by single-weighted weighting method in study of conventional risk assessment, and thus increasing the credibility and reliability of risk assessment in index analysis. These results can be used to help avoid the risk of cold damage to maize, and to optimize the planting structure and layout using local climate resources, thereby ensuring the safety of maize in these growing areas. In the future, selection of assessment indices and establishment of a comprehensive assessment system still needs further in-depth exploration.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

This study was supported by the National Science and Technology Support Program, project number 2012 BAH29B00.

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Received: July 05, 2015 Revised: August 15, 2015 Accepted: September 11, 2015