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ORIGINAL PAPER

Quantitative assessment and spatial characteristic analysis of agricultural drought risk in China

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Abstract Based on the natural disaster analysis theory, the spatial characteristics of agricultural drought risk in China were investigated at 10 × 10 km grid scale. It shows that agricultural drought risk in China has a clear southeast–northwest spatial pattern. High and very high risk mainly occur in the eastern part of Northeast Plain, the central of Inner Mongolian Plateau, the Loess Plateau, north Xinjiang, the north and south of Yangtze Plain, and Yunnan-Guizhou Plateau. Statistics also show that 19.5 % of the main crop planting area is exposed to low risk, 35.1 % of the area to moderate risk, 39.8 % of the area to high risk, and 5.6 % of the area to very high risk. Further investigation shows that 23 % of total wheat growing areas is located in high and very high risk class; corn and rice are 16 % and 14 % respectively. Comprehensive analysis shows that severely affected areas by drought in the history are mainly located in the high and very high risk areas.

Keywords Agricultural drought · Risk assessment · Spatial characters

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1 Introduction

Drought is one of the world's costliest natural disasters and affects a very large number of people each year (Wilhite 2000; Walter 2004). With the increasing loss and social vulnerability to drought, drought management posed a great challenge to the world. In recent years, many governments and others are striving to develop national drought policies and preparedness plans that place emphasis on risk management rather than following the traditional approach of crisis management, where the emphasis is on reactive, emergency response measures (Wilhite 2000; Sivakumar and Wilhite 2002). Drought risk analysis is needed to help better understand a region's drought vulnerability and identify the appropriate mitigation actions to take (Hayes et al. 2004).

Generally, drought risk is considered to be the product of the hazard and vulnerability (risk = hazard × vulnerability) (Knutson et al. 1998; Downing et al. 1999; Downing and Bakker 2000; Wilhite 2000). In recent decade, a number of studies have been carried out on the theory and methods for the evaluation of drought risk. For example, in Hayes et al. (2004) study, a framework of drought risk analysis was been proposed and widely used in related studies. Furthermore, the quantitative assessment of the drought vulnerability, hazard, and risk has been conduct many area, such as America (Wilhelmi and Wilhite 2002), Bangladesh (Shahid and Behrawan 2007), Namibia (Persendt 2009), and so on. In addition, MEDROPLAN(Mediterranean Drought Preparedness and Mitigation Planning)was carried out to develop the methodological framework for risk-based approach to drought management in Mediterranean Countries. Drought risk analysis has been conducted case studies in its member countries Slovakia, Italy, Spain, etc. (Ameziane et al. 2007).

China is a drought-prone country, and agriculture is the worst drought-affected sector (He et al. 2011). The economic losses from the 2009 drought in China alone have been estimated at more than 150.9 billion RMB. A number of studies have been carried out on drought monitor (Li et al. 1996, 2003; Ju et al. 1997) and impact of droughts on agriculture (Fu 1991; Fang et al. 1997; Wang et al. 2002); however, to author's knowledge, there has been no standard methodology for national assessment of droughts risk in China. The main objective of this study is to assess the agricultural drought risk in China. Based on the theory of natural disaster analysis, the spatial variance of agricultural drought risk in China will be analyzed using a 10-km grid-cell scale in this study. Furthermore, the spatial pattern of China agricultural drought will be explored, and the risk map will be created, which is crucial for China agricultural drought risk management and water resource management.

2 Data and methodology

2.1 Data and processing

Table 1 lists the datasets used in this study. To better indicate the regional distribution of the meteorological factors, the daily meteorological data during 1961–2008 of stations were interpolated into 10 × 10 km raster data by using the ANUSPLIN interpolation method (Hutchinson 1991). Figure 1 shows the spatial pattern of annual rainfall during the past 50 years over China. Using the same method, the phenological data of three main food crops (wheat, corn, rice) and the distribution data of the three crops extracted from the 1:100 million vegetation map of China were also processed into 10 km × 10 km raster data. The soil AWC data and the irrigation area data for China with 10-km resolution were extracted from the Global Profile Available Soil Water Capacity and Global Irrigation Area Map respectively.

Table 1 Datasets used in this study

Daily meteorological data for the period of 1961–2008 from 720 rain-gauge stations in China. (Data included precipitation, highest temperature, lowest temperature, average temperature, relative humidity, wind speed, rainfall, and the altitude, latitude, and longitude of each station)	Offered by China Meteorological Data Sharing Service System http://cdc.cma.gov.cn/
Crop phenology data (wheat, corn, and rice)	China Agricultural Phenology Atlas (Zhang et al. 1987)
1:100 million vegetation map of China	Provided by Data Sharing Infrastructure of Earth System Science (http://www.geodata.cn/)
Global profile available soil water capacity	Issued by International Geosphere–Biosphere Program (http://www.igbp.net/)
Global irrigation area map (GIAM10 km-8classes: Version2.0)	Issued by International Water Management Institute (http://www.iwmigiam.org)

2.2 Methodology

Based on disaster risk analysis theory, three components determine the risk; they are hazard, vulnerability, and exposure (Hochrainer 2006). Drought risk is a product of a region's exposure to the natural hazard and its vulnerability to extended periods of water shortage (Wilhite 2000). Therefore, a conceptual approach to risk assessment can be split into hazard and vulnerability. A conceptual model of agricultural drought risk assessment was constructed as follows:

$$R = G(f(h), f(v)) \tag{1}$$

where, R is the agricultural drought risk, G is the conceptual function for agricultural drought risk assessment and is the combination of $f(h)$ and $f(v)$, $f(h)$ is the function of agricultural drought hazard, and $f(v)$ is the function of agricultural drought vulnerability.

2.2.1 Agricultural drought hazard analysis

The severity of drought depends upon the duration, intensity, and spatial extent of a specific drought episode (Sonamez et al. 2005; Wilhite 2000). A drought hazard assessment model that developed based on a world popular drought index SPI (standardized precipitation index) in a GIS environment is applied to map the spatial extent of China agricultural drought hazard. A main advantage of SPI is its variable time scales, and generally, the SPI on shorter time scale describes drought events affecting agricultural practices. So a 3-month step SPI was selected in this study to explore China agricultural drought hazard characters. Using the 50-year precipitation data with 10×10 km resolution, the SPI was calculated, and drought occurrence and serenity were identified for each single grid. In the model, each drought severity theme calculated by SPI was given a particular weight using the value from one to three, with level one relating to the lowest agricultural drought severity; furthermore,

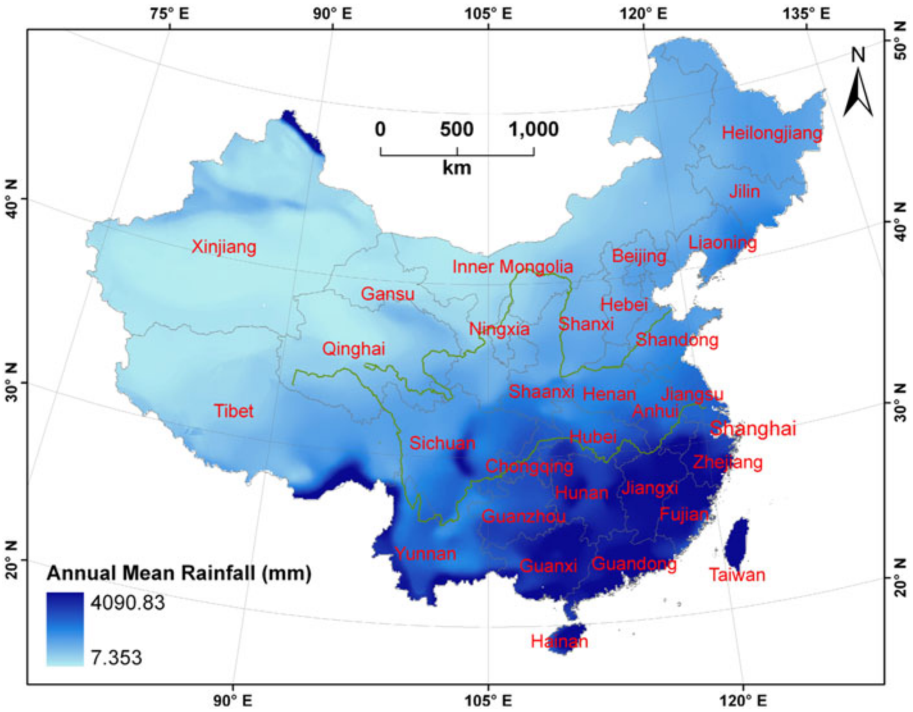

Fig. 1 Spatial pattern of annul rainfall over China

the occurrences of moderate, severe, and extreme drought were calculated and classified into four classes using natural breaks method, and each class of the theme was given a rating from one to four, with high value means the high drought occurrence. Drought hazard index (DHI) was calculated as follows:

$$DHI = (MD_r \times MD_w) + (SD_r \times SD_w) + (VD_r \times VD_w) \quad (2)$$

where, DHI is the drought hazard index; MD_r is the ratings assigned to moderate droughts occurrence classes; MD_w is the weight given to the theme of moderate drought occurrence theme; SD_r is the ratings assigned to severe droughts occurrence classes; SD_w is the weight given to the theme of severe drought occurrence theme; VD_r is the ratings assigned to very severe droughts occurrence classes; and VD_w is the weight given to the theme of very severe drought occurrence theme.

Based on GIS, the spatial characteristics of agricultural drought hazard in China were investigated using DHI model, and to highlight the drought hazard in agricultural areas, only the main crops (wheat, rice, and corn) planting areas were extracted, as showed in Fig. 2. Detailed description of the model and data sources can be found in our previous study on agricultural drought hazard assessment in China (He et al. 2011).

2.2.2 *Agricultural drought vulnerability analysis*

Drought vulnerability is defined as the characteristics of populations, activities, or the environment that make them susceptible to the effects of drought (Knutson et al. 1998). The degree of vulnerability depends on the environmental and social characteristics of the

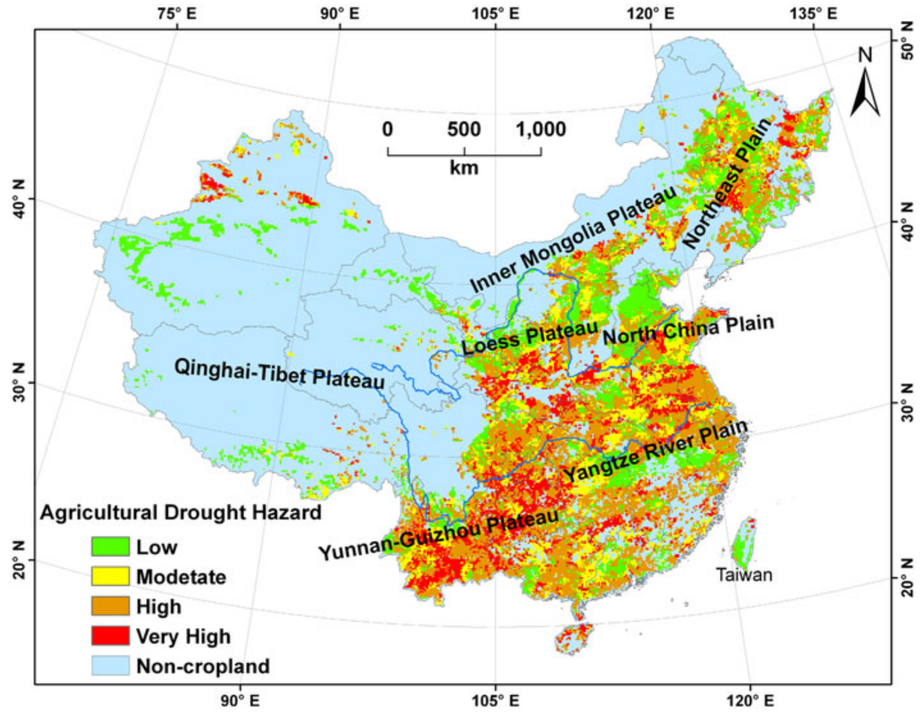

Fig. 2 *Map* showing agricultural drought hazards in China [extracted by using main crop distribution map from the hazard map drew by He et al. (2011)]. (High and very high hazard mainly occurs in the central part of Northeast China Plain, the northern part of Heilongjiang, the northern part of Xinjiang, the southeastern part of Qinghai-Tibet Plateau, the central and southern parts of Loess Plateau, the southern part of North China Plain, the northern and southern parts of Yangtze River Plain, and Yunnan-Guizhou Plateau.)

region and is measured by the ability to anticipate, cope with, resist, and recover from drought. After systematic analysis of previous studies on drought vulnerability and consideration of the availability of indicator (Wilhelmi and Wilhite 2002; Shahid and Behrawan 2007), we constructed an agricultural drought vulnerability assessment model by selecting three agricultural drought vulnerability factors; they are seasonal crop water deficiency (SCWD), available soil water-holding capacity (AWC), and irrigation (IRR) (Wu et al. 2011), among which seasonal crop water deficiency is a climate factor, reflects the difference between the crop water demand during the growing season and the precipitation during the crop growing season, high deficiency means high vulnerability; the available soil water-holding capacity is the volume of water that should be available to plants, which reflects the ability of different type of soils to buffer plants during periods of moisture deficiency; and the irrigation is an important artificial measure to resist to drought, high ratio of irrigation means high capability to withstand drought.

The model was developed as follows:

$$\mathrm{DVI} = W_{\mathrm{awc}} + W_{\mathrm{scwd}} + W_{\mathrm{irr}} \tag{3}$$

where, DVI is the agricultural drought vulnerability index, W_{awc} is the weighting of AWC, W_{scwd} is the weighting of the seasonal crop water deficiency, and W_{irr} is the weighting of irrigation availability.

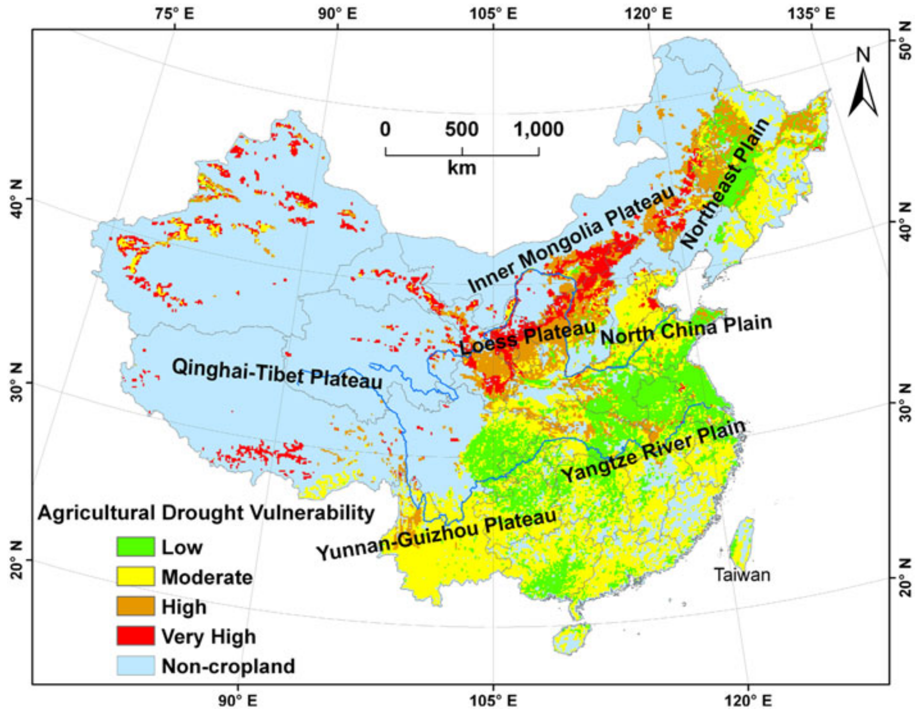

Fig. 3 Map showing agricultural drought vulnerability in China (The low- and moderate vulnerability regions are mainly distributed in the east and south of China, while the high and very high vulnerability regions are mainly distributed in the north and west.)

The seasonal crop water deficiency SCWD was calculated by a simple model as follows:

$$\mathrm{SCWD} = \frac{\mathrm{ET} - P}{\mathrm{ET}} \tag{4}$$

where, SCWD is the seasonal crop water deficiency, ET is the seasonal crop water use, and P is the precipitation during crop growing season.

Three main grain crops (wheat, corn, and rice) were selected to calculate the SCWD. The length of the crop growing season was determined according to the Chinese Agricultural Phenology Atlas (Zhang et al. 1987). ET was estimated using the mathematical model recommended by FAO (Allen et al. 1998). Then, the regional average SCWD was calculated by using model developed in Wu et al.'s (2011) study.

The available soil water-holding capacity (AWC) data and the irrigation (IRR) data for China with 10-km resolution were extracted from the Global Profile Available Soil Water Capacity and Global Irrigation Area Map respectively.

Finally, the values of SCWD, AWC, and IRR were classified into several classes and given a weighting respectively. Based on GIS, the spatial characteristics of agricultural drought vulnerability in China were investigated using the agricultural drought vulnerability assessment model (Fig. 3). Detailed description of the model and data sources can be found in our previous study on agricultural drought vulnerability assessment in China (Wu et al. 2011).

2.2.3 *Agricultural drought risk analysis*

Former study represented risk as the sum of the hazard plus vulnerability (risk = hazard + vulnerability) (Blaikie et al. 1994). More recently, the Hayes et al. (2004) study discussed different approaches and argued that drought risk is best represented as a product of hazard and vulnerability (Hayes et al. 2004), so we constructed the conceptual model as follows:

$$\mathrm{DRI} = \mathrm{DHI} \times \mathrm{DVI} \tag{5}$$

where, DRI is the agricultural drought risk index, DHI is the agricultural hazard index, the value is the class of agricultural hazard ranging from 1 to 4, for example, if the hazard class is low, the value of DHI is 1, and the very high hazard corresponds to 4; DVI is the agricultural vulnerability index, the value is the class of agricultural vulnerability ranging from 1 to 4 similar to DHI value.

Using this model, the agricultural drought hazard and vulnerability maps will be integrated in GIS environment, and the agricultural drought risk for each single grid will be calculated. Finally, the value of DRI will be classified to four classes by using natural breaks method to produce the composite drought risk map of China.

3 Results

3.1 Spatial characteristics of drought risk in China

Using the agricultural drought risk evaluation model established by this paper, the agricultural drought risk was assessed at a 10-km grid scale. The spatial pattern of agricultural drought risk in China shows southeast–northwest difference (Fig. 4), with the low- and moderate risk areas that are mainly in the eastern and southern parts of China, while the areas with high and very high risk to drought are mainly concentrated in the western and northern parts.

Percentage of area under different drought risk categories in China is given in Table 2. Statistics show that 19.5 % of the main crop planting area is exposed to low risk, 35.1 % of the area to moderate risk, 39.8 % of the area to high risk, and 5.6 % of the area to very high risk. The low and moderate risk areas are mainly found in the northern and southern parts of Northeast China Plain, the central of North China Plain, central part of Yangtze River Plain, western part of Chengdu Plain, and the southern part of Guangxi Province. High and very high risk mainly occurs in the east of Northeast Plain, the central of Inner Mongolian Plateau, the Loess Plateau, north Xinjiang, the north and south of Yangtze Plain, and Yunnan-Guizhou Plateau.

Low available soil water-holding capacity and dependency on irrigation alone with high variability of annual rainfall has made the northwestern parts highly risky to droughts compared to other parts of the country. Water conservation is essential to reduce the drought impact in the area. The reason to high risk in the southwest of China is mainly the high occurrence of drought and the difficultly to access to irrigation due to large terrain gap, building water conservancy projects maybe the main way to reduce the risk.

We also explored the areas of different crops exposed in high and very high class by overlapping the main crop distribution map with the agricultural drought risk map. Statistic shows that 23 % of total wheat growing areas is located in high and very high risk class;

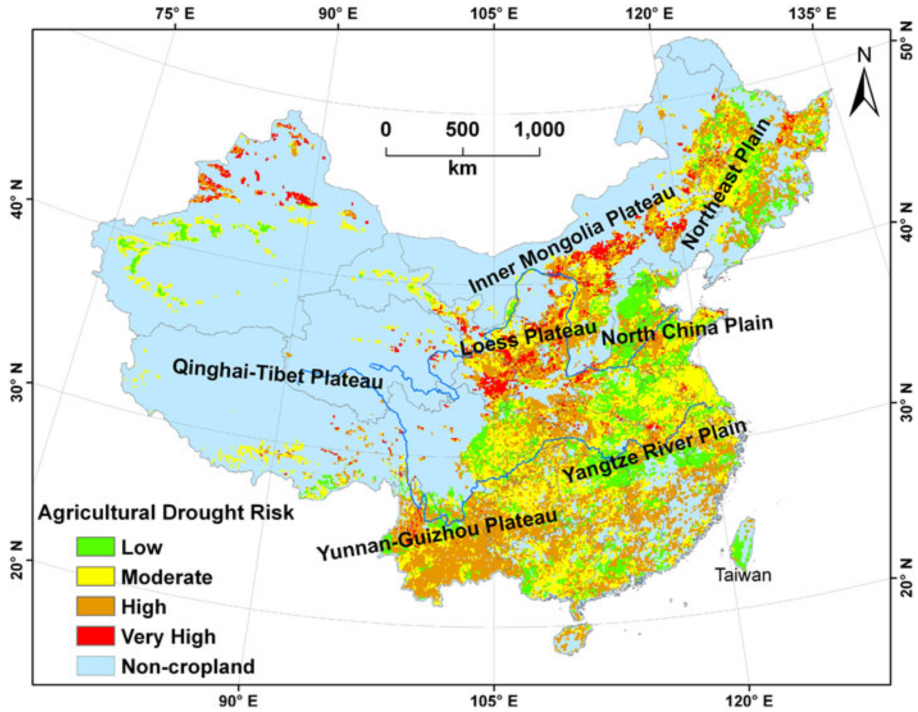

Fig. 4 Map showing agricultural drought risk in China

Table 2 Ratios of main crops planting area under different risk levels

Agricultural drought risk	Ratios of main crops planting area under different risk levels (%)
Low	19.5
Moderate	35.1
High	39.8
Very high	5.6

corn and rice are 16 % and 14 % respectively. Therefore, we can say that drought posed a great threat to main food crops production.

3.2 Validation

Drought disaster information is a direct reflection of drought impact. During the past two decade, a number of studies have been carried out on the temporal and spatial patterns of drought (Fu 1991; Pan et al. 1996; Fang et al. 1997; Wang et al. 2002; Li et al. 1996) using drought disaster information data, which are composed of the time of drought occurrence, intensity, duration, affected area, grain loss, and so on. For example, Wang et al.(2002) explored the spatial distribution characters of drought in China according to the statistical drought loss data and identified Several heavy drought centers: in the north of China, they are the western part of Hei Longjiang province, the central of Inner Mongolia province, the northern part of He Bei province, the northern part of Shan Xi province and Ningxia province; in the south of China, they are concentrated in the province of An Hui, Hu Bei, Hu Nan, He Nan, the eastern part of Si Chuan, and the central and eastern part of Gui Zhou and Yun Nan province. In addition, serious repeated droughts hit China in recent years, such as the Yunnan-Guizhou Plateau suffered severe drought in 2010 and 2012, and caused tremendous loss to agriculture; the same tragedy was also happen in Inner Mongolia and south of Yangtze Plain in 2011. Comparing to the results of previous study and the drought events in recent years, we can find that areas where were seriously affected by drought in the history are mainly located in the high risk areas.

Some areas, such as the Chengdu Plain, although classified in the low- or moderate risk category, are also the serous drought-hit areas. There may be two reasons: first of all, these regions mainly located in plains, where are the main grain production areas. When droughts occurred, the high exposure of these areas often resulted in high losses. Second, these regions are usually irrigation available areas. However, due to irrational use of water resources and serious water pollution, leading to sharp decrease of water resources. When a serious drought happened, irrigation areas reduced significantly and increasing crop failure.

3.3 Different types of agricultural drought risk

Risk analysis is the foundation for agricultural drought risk management, and risk is the combination of hazard and vulnerability. For a region, the high hazard areas may correspond to high vulnerability area and also may be low vulnerability area. For different combinations of the hazard and vulnerability, the way to reducing the risk may be not the same. Therefore, we divided Chinese agricultural drought risk into four types as shown in Fig. 5 to implore the policy of drought management according to the combination characters of the hazard and vulnerability. The way to make the map is as following. Firstly, we reclassified the hazard map and vulnerability map into 2 classes respectively. Second, 1 and 2 were assigned as the hazard class numbers, 1 represented low hazard class and 2 represented high hazard class; Similarly, 3 was assigned to represent low vulnerability and 4 to represent high vulnerability. Third, the new hazard map and the vulnerability map were overlapped using the formula of “Risk = hazard vulnerability”. Finally, the risk-type map was made and we got four new risk value; they were 3, 4, 6, and 8, represented low hazard-low vulnerability, low hazard-high vulnerability, high hazard-low vulnerability and high hazard-high vulnerability respectively.

1. High hazard-high vulnerability region. The Loess Plateau represented this type and where was characterized with high frequency and intensive droughts, water resource shortage, and serious soil erosion. As difficult to access to irrigation, crop yields in these region are low and with high fluctuation. Reducing risk in this area should rely on ecological protection, planting structure adjustment, and drought-resistant crop selection. In addition, the implementation of integrated development of agriculture, forestry, and animal husbandry is an effective way to reduce the effects of drought.
2. High hazard-low vulnerability region. The central of Northeast China Plain is a typical area in this region. These areas often have ideal natural conditions, such as abundant water and heat resource. However, the high class of drought hazard may also cause serious impacts to agriculture. Improving drought monitoring and early warning capabilities and strengthening irrigation and water conservancy projects can effectively ensure high-yield agriculture.

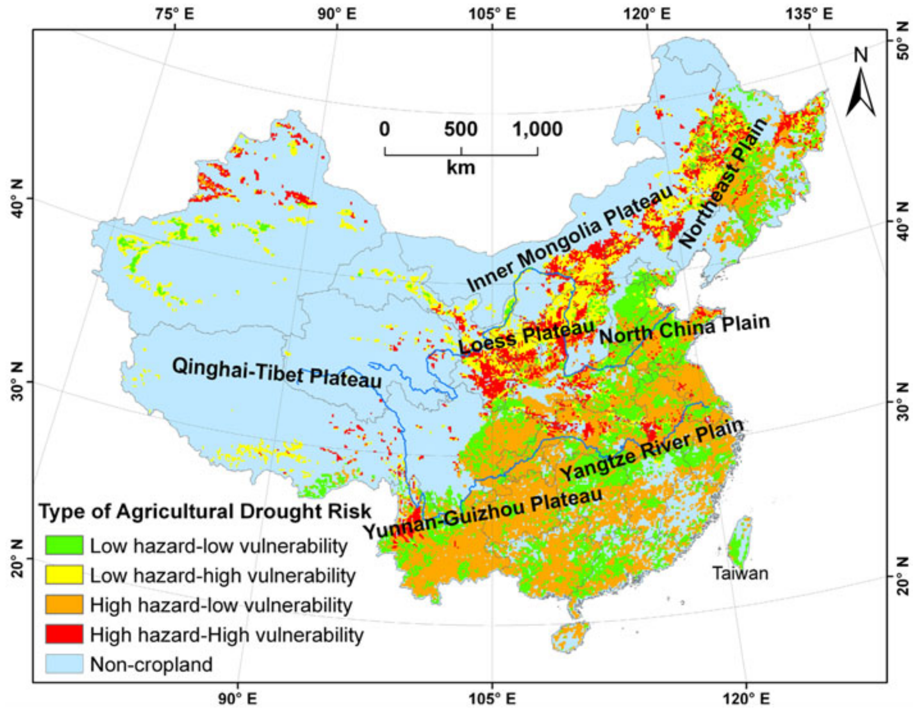

Fig. 5 Map showing different types of agricultural drought risk

3. Low hazard-High vulnerability region. This region is characterized with low drought concurrency and intensity, but due to the high vulnerability, it also could be high loss area, such as the southern part of Xinjiang. The reduction in agricultural drought risk in these areas should depend on enhancing water conservation and water-saving techniques, adjusting planting structure, which can effectively reduce the agricultural drought vulnerability.
4. Low hazard-low vulnerability region. This region is the most favorable areas for agricultural production, such as the central of Yangtze River Plain (the northeast of Hunan province and the north of Jiangxi province). However, for the high intensity of agricultural productions often concentrated in this region, a serious drought may be caused a large amount of agricultural losses. So the accuracy and timely drought monitoring and early warning are crucial for protecting the agricultural productions from drought impact in this region.

We analyze the formation processes of different types of agricultural drought risk and attempt to explore the appropriate management measure in the above. We hope that the risk map can really serve in the identification and management of agricultural drought risk in the future.

4 Conclusion

Drought is the main disaster which affects agricultural production in China. It is very important for China to carry out the agricultural drought risk analysis to reduce the impacts of drought. Based on the main principle of drought risk analysis, we assessed the overall characteristics of drought risk in China at a 10-km grid scale by using a conceptual model. Furthermore, the way to reduce the regional agricultural drought risk is also explored according to the type of risk.

The spatial distribution of agricultural drought risk in China shows apparent southeast–northwest differences. High and very high risk mainly occurs in the east of Northeast Plain, the central of Inner Mongolian Plateau, the Loess Plateau, north Xinjiang, the north and south of Yangtze Plain, and Yunnan-Guizhou Plateau. Statistics also show that 19.5 % of the main crop planting area is exposed to low risk, 35.1 % of the area to moderate risk, 39.8 % of the area to high risk, and 5.6 % of the area to very high risk. Comprehensive analysis shows that areas where were seriously affected by drought in the history are mainly located in the high risk areas.

At a grid scale, we can study agricultural drought risk moving from points to spaces and from small areas to large areas. In addition, the agricultural drought risk in China is divided into four types, and the strategies for responding to drought are explored to each category, which could provide essential information to help for the policy formation of Chinese agricultural drought risk management.

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