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Quantitative assessment and spatial characteristics analysis of agricultural drought vulnerability in China

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Abstract In this study, the spatial characteristics of agricultural drought vulnerability in China were investigated using a GIS-based agricultural drought vulnerability assessment model, which was constructed by selecting three agricultural drought vulnerability factors. Seasonal crop water deficiency, available soil water-holding capacity and irrigation were identified as the main indicators of agricultural drought vulnerability in China. The study showed that the distribution of seasonal crop moisture deficiency showed significant differentiation in both north–south and east–west directions, and the agricultural drought vulnerability presented a similar trend. At a regional scale, southern and eastern China typically has a low- and moderate-vulnerability to drought, while high and very high vulnerability to agricultural drought is observed in northern and western China. In terms of China's agricultural regions, the central part of the southwest region, the area between the southern Huang-Huai-Hai region and the northern part of the Middle and lower reaches of the Yangtze River region, and the northeast region are the areas of low agricultural drought vulnerability in China, while areas of high agricultural drought vulnerability are mainly located in the Inner Mongolia, Loess Plateau and Gan-Xin regions. Due to differences in the physical and social–economic conditions within the agricultural areas, vulnerability to agricultural drought exhibits substantial variability both between different agricultural regions and within the same region. The methodology of grid-cell-based agricultural drought vulnerability assessment, developed in this study, provides a foundation for better description of the differences in regional and even smaller scale.

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1 Introduction

Drought is a normal recurrent feature of climate, and is considered by many to be the most complex but least understood of all natural hazards, affecting more people than any other hazard (Hagman 1984). The data from Emergency Events Database (www.em-dat.net) show that, throughout the world, droughts account for 5% of the natural disasters, but losses from droughts have caused up to 30% of all losses from disasters, ranking droughts first among all the natural hazards. Furthermore, with the escalation of global climate change, the frequency of droughts and the areas affected are expected to increase sharply (NCAR 2005; IPCC 2001). Worldwide losses from droughts have increased significantly in tandem with the increased number and severity of droughts (Wilhite 2000). The high economic cost and social vulnerability to droughts has led to increasing attention to the issue of drought vulnerability in recent years (Wilhite 1993, 2000; Keenan and Krannich 1997; Downing and Bakker 2000).

Vulnerability assessment provides a framework for identifying the social, economic and environmental causes of drought impacts. It is one of the main aspects of drought planning and mitigation (Wilhite 1993, 2000; Knutson et al. 1998), and bridges the gap between impact assessment and policy formulation by directing policy attention to underlying cause of vulnerability rather than the negative effects which follow triggering events such as droughts (Ribot et al. 1996). With a map of drought vulnerability, decision-makers can visualize the hazard risk and convey vulnerability information to other sectors to ensure that they will act in a timely and effectively way to tackle drought-related losses (Wilhelmi and Wilhite 2002).

Beginning in the 1980s, the study of social, economic and environmental vulnerability to disasters has become an important subject, and many scholars have carried out research on this (Kates 1985; Blaikie et al. 1994; Keenan and Krannich 1997; Downing and Bakker 2000). Downing and Bakker (2000) argue that vulnerability is a relative measure, therefore critical levels should be defined; however, because of the complexity of the issue of vulnerability, assessments can be complicated and are not always well understood, especially for vulnerability to drought, which still lacks a universal definition and onset criteria (Wilhite 1993, 2000). Vulnerability to drought is dynamic and is influenced by a multitude of factors, including increases and regional shifts in population, urbanization, technology, government policies, land use and other natural resource management practices, desertification processes, water-use trends, and increasing environmental awareness (Wilhite 2000). The Western Drought Coordination Council (WDCC) has defined drought vulnerability as follows: Characteristics of populations, activities, or the environment that make them susceptible to the effects of drought. The degree of vulnerability depends on the environmental and social characteristics of the region and is measured by the ability to anticipate, cope with, resist and recover from drought (Knutson et al. 1998). Additionally, WDCC developed a series of tree diagrams to demonstrate potential drought impacts, from which true drought vulnerabilities can be identified and subsequently addressed. In recent years, scholars have actively explored the methodology and techniques for quantitative agricultural drought vulnerability assessments (Wilhelmi and Wilhite 2002; Shahid and Behrawan 2007; Bella et al. 2005). The general method involves identifying vulnerability indicators to construct a drought vulnerability index, and using GIS techniques to develop thematic maps. The Wilhelmi and Wilhite (2002) study provides the starting point for the examination of drought vulnerability, this was done by using a weighted combination of data on probability of moisture deficiency, capacity of the soil to hold water, land use and irrigated cropland with the classes within each factor being assigned a vulnerability ranking. In this study, the drought vulnerability for a given area (Nebraska State) was estimated using GIS tools and RS data. To determine drought vulnerability, the most important and most difficult task is to select the factors and to determine the weighting of those factors, which are commonly subjective and may vary between regions. The main reason for this problem is that the mechanism for determining how agricultural drought vulnerability is produced is still unclear.

In China, drought is a persistent climatic problem. Droughts occur with high frequency, affecting a wide range of areas, causing huge losses in agriculture, and are currently the most serious type of meteorological disaster in China. The average area affected by drought is about 21.593 million hectares annually, accounting for 60% of the total area in China affected by all types of meteorological disasters. The annual grain losses due to drought are up to 10 billion kilograms. A number of studies have been carried out on the impact of droughts on agriculture (Fu 1991; Pan et al. 1996; Fang et al. 1997; Wang et al. 2002), and the temporal and spatial patterns of drought (Li et al. 1996), but little work has been done on the issue of agricultural drought vulnerability. The previous studies on agricultural drought vulnerability were carried out by constructing an evaluation index system and evaluation model, which were usually conducted on a relatively small scale, considering counties and provinces (Shang and Shi 1998; Shang 1999; Shang 2000a, b; Shang et al. 2006; Liu et al. 2002, 2005; Wang et al. 2005a, 2006; Su et al. 2005). These results met the needs of regional agricultural drought management, but due to the weak understanding of the potential cause of drought vulnerability, the indicators that were selected are subjective and too complicated to be applied in larger areas. There is an urgent need to construct a nationwide agricultural drought vulnerability map to enhance agricultural drought management.

The goal of this study is to determine key factors that contribute to agricultural drought vulnerability and to construct a grid-cell-based agricultural drought assessment model for major food crops (wheat, corn and corn) using a GIS environment. The advantage of this grid-cell analysis approach is that results are spatially continuous. The spatial variance of agricultural drought vulnerability in China will be analyzed using a 10-km grid-cell scale. Furthermore; we will explore an effective method to reduce the agricultural drought vulnerability, providing scientific guidance for the defense and mitigation of agricultural droughts, and protecting food production from drought.

2 Data and methodology

2.1 Methodology

2.1.1 Agricultural drought vulnerability indicator selection and calculations

A holistic drought vulnerability index should take into account the ecological, socio-economic and production conditions. However, indicators for all these conditions are not readily obtainable and/or quantifiable in China. After careful consideration of previous studies on drought vulnerability and obtainable and quantifiable socio-economic and physical indicators, three indicators were identified as important and pertinent to this study and were subsequently selected to represent the vulnerability to agricultural drought. These indicators are climate, soil and irrigation represented by seasonal crop water deficiency, soil water-holding capacity and irrigation availability, respectively. Based on the assumption that China's agricultural drought vulnerability is affected by all three factors, we constructed the conceptual model for agricultural drought vulnerability assessment as follows:

$$V = G(f(C), f(S), f(I)), \tag{1}$$

where V is the agricultural drought vulnerability, $f(C)$ is the function of the climate factor, $f(S)$ is the function of the soil factor; and $f(I)$ is the function of the irrigation factor.

2.1.1.1 Climate Agricultural drought becomes apparent when soil water decreases. The soil water condition was mainly determined by the balance between precipitation and evapotranspiration. In this study, we used the seasonal crop water deficiency (SCWD) to represent the climate indicator (Allen et al. 1998; Wilhelmi and Wilhite 2002). That is, without considering the irrigation condition, the difference between the crop water demand during the growing season and the precipitation during the crop growing season, as follows:

$$\mathrm{SCWD} = \frac{\mathrm{ET} - P}{\mathrm{ET}}, \tag{2}$$

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

Under well-watered conditions, ET was estimated using the mathematical model recommended by FAO (Allen et al. 1998), as follows:

$$\mathrm{ET} = \mathrm{ET}_0 \cdot \mathrm{Kc}, \tag{3}$$

where ET_0 is the potential evapotranspiration, which can be computed from meteorological data using the FAO Penman–Monteith method (Allen et al. 1998). This method overcomes shortcomings in the previous FAO Penman method and provides values more consistent with actual worldwide crop water-use data. It is popularly used and accurate for both arid and humid conditions. Studies carried out by Wu et al. (2005) and Yin et al. (2005) showed that it is also suitable for China. The model is as follows:

$$\mathrm{ET}_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}, \tag{4}$$

where Δ represents the slope of the saturation vapor pressure–temperature relationship (kPa/°C^{-1}), Rn is the net solar radiation (MJm^{-2}d^{-1}), G is the soil heat flux (MJm^{-2}d^{-1}), γ is the psychrometric constant (kPa/°C^{-1}), T is mean daily air temperature at 2 m height (°C), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure deficit (kPa) and U_2 is the wind speed at 2 m height (m s^{-1}).

In this model, the empirical parameters for solar radiation have been modified (Wang 1981; Wang et al. 1988; Zuo et al. 1993; Wu et al. 2005), making it more consistent with conditions in China. In this study, we used the modified model to calculate ET_0.

Kc is a crop coefficient, determined from independent experiments by examining the ratio of ET–ET_0 in various growth stages for a well-watered crop. Although the Kc values for main food crops (wheat, corn and rice) have been reported by FAO, additional research has been conducted on the Kc value of main food crops in China (Chen 1995; Liu et al. 1998; Lei et al. 1999; Liu and Pereira 2000; Sun et al. 2002; Zhang et al. 2002; Peng et al.

2007; Wang et al. 2005b; Liu and Kang 2006; Yang et al. 2006). Our study uses the modified Kc value for the three food crop (wheat, corn and rice) based on the above research.

At a regional scale, we use the following formula to calculate the area-weighted mean, ET, as follows:

$$\overline{\mathrm{ET}} = \frac{\mathrm{ET}_w * \rho_w + \mathrm{ET}_c * \rho_c + \mathrm{ET}_r * \rho_r}{\rho_w + \rho_c + \rho_r}, \quad (5)$$

where ET_w, ET_c and ET_r are the seasonal water uses of wheat, corn and rice, respectively; ρ_w, ρ_c and ρ_r are the proportions of land under wheat, corn and rice compared with the total area of cropland in a single grid cell, the grid-cell size is 10 × 10 km.

Finally, the regional $\overline{\mathrm{SCWD}}$ is calculated using following model.

$$\overline{\mathrm{SCWD}} = \frac{\overline{\mathrm{ET}} - P}{\overline{\mathrm{ET}}}. \quad (6)$$

2.1.1.2 Soil The available water-holding capacity (AWC) of soil is the volume of soil water that should be available to plants, which reflects the ability of different types of soils to buffer plants during periods of moisture deficiency. AWC is an important soil property and is commonly estimated as the difference in water content between field capacity and permanent wilting point with corrections for salinity, fragments and rooting depth (Scotter 1981). Studies show that AWC depends largely on soil porosity, which, in turn, depends on soil texture, structure, organic matter, bulk density and other parameters (Wilhelmi and Wilhite 2002; Marshall 1979).

The amount of available water that the soil can supply may be critical to sustain plants between rainfall events or periods of irrigation, as the soil effectively buffers the plant root environment against periods of water deficit (http://soils.usda.gov). Furthermore, the geographic pattern of soil water-holding capacity is also important for studying water stress in plants and is critical to water management planning for irrigation and dryland crops (Kern 1995; Klocke and Hergert 1990). For these reasons, we selected the AWC of soil as an important agricultural drought vulnerability indicator. Regions with low AWC values have a higher degree of agricultural drought vulnerability when compared with regions with high AWC values.

2.1.1.3 Irrigation Irrigation is one important strategy to defend against and mitigate drought, and it is also important for improving crop yields, protecting water supplies, ensuring food security, increasing income and improving the ecological environment. Agriculture accounts for about 70% of all water use worldwide. Although the worldwide irrigated land accounts for only 18% of the total agricultural land, the grain output from irrigated land comprises 40% of the total grain output. In China, the spatial distribution of water resources does not match the distribution of cultivated land, water resources are distributed with 20% of the total in the north of China and 80% in the south, while the cultivated land is distributed with 62 and 38% in the north and south, respectively (Gao 2006). With this distribution pattern, irrigation is essential for agricultural production, and in this study, we assume that the access to irrigation effectively reduces drought impact and that irrigated lands have a lower drought vulnerability compared with rain-fed dry lands during short-term drought conditions.

Table 1 Weighting scheme for assessing agricultural drought vulnerability in China

Agricultural drought vulnerability factor	Vulnerability class	Weight
Soil AWC	<100 mm	4
	100–175 mm	3
	175–250 mm	2
	>250 mm	1
Seasonal crop water deficiency	<0	2
	0–30%	3
	30–60%	4
	>60%	5
Irrigation support	Available irrigation	1
	No irrigation	4

2.1.2 Agricultural drought vulnerability assessment model

Based on the studies of scholars in China and internationally (Wilhelmi and Wilhite 2002; Shahid and Behrawan 2007; Bella et al. 2005; Liu et al. 2002; Shang 2000a, b), we set the weightings of the agricultural drought vulnerability factors using the following method (Table 1). Each of the selected indicators was divided into four classes, ranging from the lowest to the highest values. Then a weight was applied to each class using the value range from one to five, with level one relating to the lowest agricultural drought vulnerability, and level five the highest agricultural drought vulnerability. The choice of weights and the weight ranges was based on an informed assumption based on the relative contributions of each factor to the overall agricultural drought vulnerability. For example, compared with soil AWC, the climate condition may play a more important role in agricultural drought vulnerability, so the range of the climate condition weights are two to five, while the soil weights are one to four. Additionally, the availability of irrigation support is also given weights from one and four, which indicates the significant difference in the ability to withstand the lack of precipitation between dryland and irrigated land.

Finally, we developed the agricultural drought assessment model as follows:

$$\mathrm{DVI} = W_{\mathrm{awc}} + W_{\mathrm{scwd}} + W_{\mathrm{irr}}, \tag{7}$$

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.

Based on GIS, a composite vulnerability map was generated by integrating the thematic maps of all indicators. The composite agricultural drought vulnerability index (DVI) for each single grid was calculated using Eq. 7. For example, for a single grid, if the W_{awc} is 2, W_{scwd} is 3 and W_{irr} is 4, then the final *DVI* for this grid is $2 + 3 + 4 = 9$. Finally, the value DVI was classified to four classes from high to low, identifying geographic areas with 'low', 'moderate', 'high' and 'very high' vulnerability. The natural break method was used to derive the classes. This method creates ranges according to an algorithm that uses the average of each range to distribute the data more evenly across the ranges. This method ensures that the ranges are well represented by their averages and that the data values within each range are fairly close together (Smith 1986).

Table 2 Data Sources

Data	Data resource
Daily meteorological data for the period of 1961–2000 from 720 rain-gauge stations in China (data included precipitation, highest temperature, lowest temperature, average temperature, relative humidity, wind speed, rainfall, 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)
Agricultural zoning data	Prepared from Data Sharing Infrastructure of Earth System Science http://www.geodata.cn/
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 Programme (http://www.igbp.net/)
Global Irrigation area map (GIAM 10 km-8 classes: version 2.0)	Issued by International Water Management Institute (http://www.iwmigiam.org)

2.2 Data and processes

2.2.1 Data

A large number of data were used in this study including meteorological data, crop phenological data, agricultural zoning data and crop distribution data, which were used to calculate the seasonal crop water deficiency. Nationally available soil AWC data and national irrigation data were also prepared for the computation of agricultural drought vulnerability. The sources of all data used in this study are listed in Table 2.

2.2.2 Data processing

To describe the spatial characteristics of agricultural drought vulnerability in China, using the Arc-GIS software package. Arc-GIS is an integrated collection of GIS software products that provides a standards-based platform for spatial analysis, data management and mapping. This study used a 10 km $\times$ 10 km grid cell as the computing units for the assessment of agricultural drought vulnerability in China. Consequently, all original data were processed into 10 km $\times$ 10 km raster data, using the following process: The daily meteorological (point) data were spatially interpolated using the ANUSPLIN interpolation method (Hutchinson 1991), to generate raster meteorological data with spatial resolution = 10 km. Using the same method as the analysis of climate, the ecological zoning of crops and the phenological data of three main food crops (wheat, corn, rice) were digitized in Arc-GIS to generate 10 km $\times$ 10 km raster data of crop phenology. The spatial distribution data for wheat, corn and rice were extracted from a 1:100 million vegetation map of China, and the area ratio of each crop in a 10 km grid cell was calculated using the method developed by Liu et al. (2003). The soil AWC data and the irrigation area data for China were extracted from the Global Profile Available Soil Water Capacity and Global

Irrigation Area Map, respectively, and the extracted AWC data were reclassified into four classes using the natural breaks method.

3 Results

3.1 Spatial pattern of water deficiency ratio of principal crops in growing season

In this study, the seasonal crop water-deficiency ratio was used to track rainfall amounts related to crop phenological requirements and to provide a scientific basis for enhancing regional water use efficiency and developing water-saving agriculture. The 40 years average of SCWD for wheat, corn and rice during 1961–2000 was calculated using Eqs. 2–4, respectively. The digital maps at 10 km resolution for SCWD are shown below (Figs. 1, 2, 3). Crop distribution varies due to the climatic differences between northern and southern China. In the north, the weather is too dry and cold for rice cultivation, and the main food crop is wheat, while in the south it is warm and wet enough for the rice cultivation. Corn is widely distributed in China. According to the analysis results, the distributions SCWD for the main food crops all show a significant spatial variance. Generally, the SCWD values to the south of the line formed by the Qinling Mountains and Huai River and in the eastern part of northeast China are high, and SCWD values gradually increase from south to north and from east to west.

The areas with high SCWD for wheat are mainly distributed to the north of the line between the Huai River-Qinling Mountains, in northwest China and the Yunnan-Guizhou Plateau, which is located in southwest China. For the rice planted in the south of China, the

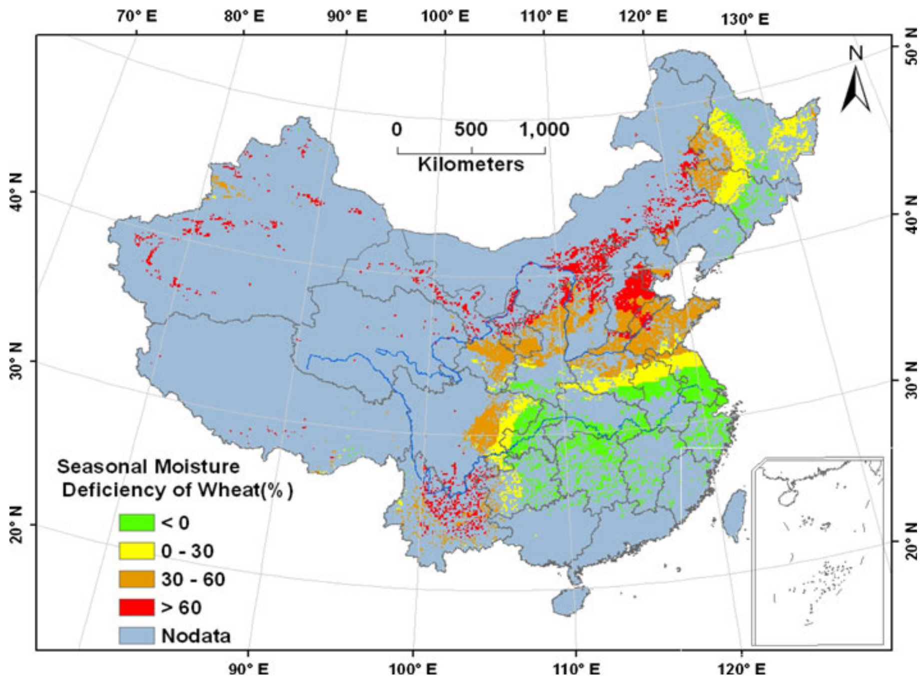

Fig. 1 Spatial variation in seasonal moisture deficiency of wheat in China

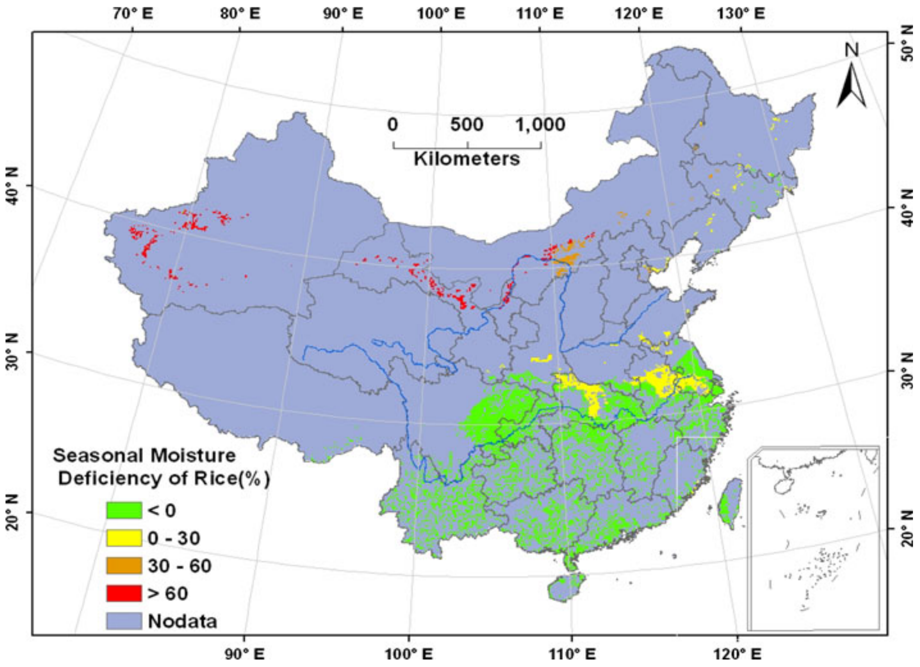

Fig. 2 Spatial variation in seasonal moisture deficiency of rice in China

rainfall during the growing season can typically meet the water requirements for rice, but in the north of China, rice has a relative high SCWD. The SCWD of corn is low in most area except for Xinjiang and the northeast of Inner Mongolia.

Using the 40 years average SCWD data for wheat, corn, rice and the plant area ratio for the three crops in each grid cell, the 40 years average crop SCWD was calculated using Eq. 6 and then classified into four levels from low to high (Fig. 4) at 10-km spatial resolution. As shown in Fig. 4, the SCWD shows an increasing trend from south to north and from east to west. The line along the Huai River-Qinling Mountains acts as a boundary, with the southern area having low SCWD values, as the rainfall can meet the crop water requirements in the growing season, while most of the northern area has high SCWD values, as the rainfall cannot satisfy the crop water needs during the growing season. The SCWD also shows significant variance from east to west, increasing gradually as a result of China's terrain features that have three terrain steps. The areas with low SCWD values are mainly distributed to the south of Huai River-Qinling Mountains, the east of the Qinghai-Tibet Plateau and in the north of northeast China. The regions with high and very high SCWD values are mainly in the west of the Northeast Plain, and south of the Inner Mongolia Plateau, almost all of the Loess Plateau, Gan-Su Corridor, Xinjiang and Tibet. Finally, areas with moderate SCWD values are mainly located in the intermediate zones where between areas of low and high SCWD values.

The spatial pattern of SCWD of major crops was consistent with the distribution of the aridity/humidity status of the land surface across China (Wu et al. 2005). In humid regions, precipitation can generally satisfy the crop water requirements in the growing season, while in arid and semiarid regions there is a large deficit between water requirement of crop and precipitation in growing season. The boundary between arid and humid areas

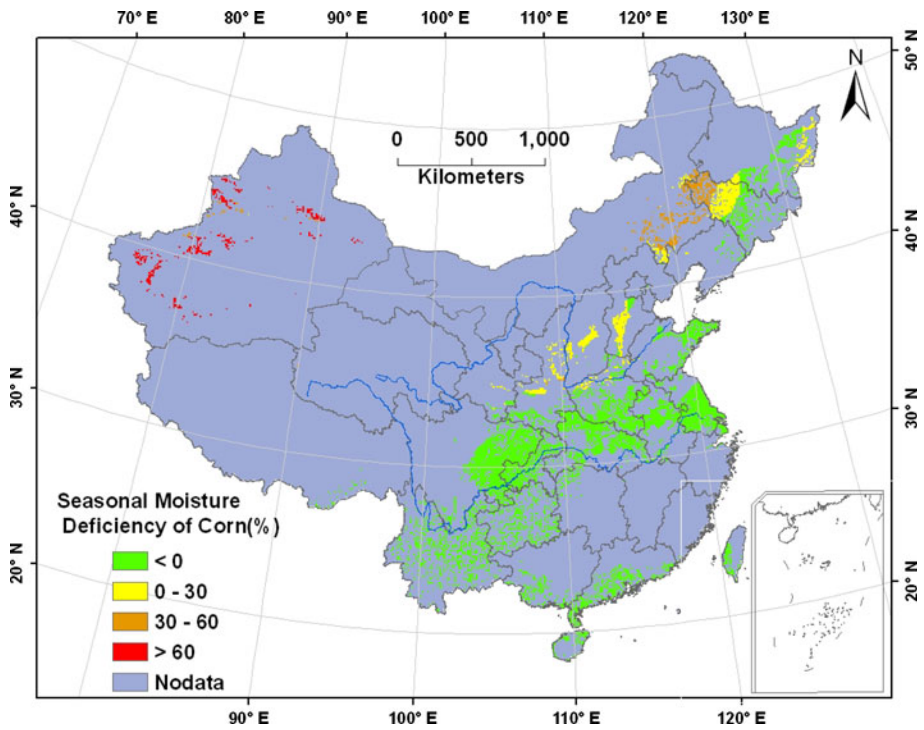

Fig. 3 Spatial variation in seasonal moisture deficiency of corn in China

often corresponds to the boundary between high and low SCWD areas, and this phenomenon is especially obvious in northeast China and the Qinling-Huaihe region.

3.2 Spatial pattern analysis of agricultural drought vulnerability

Using the agricultural drought vulnerability evaluation model established by this paper, the agricultural drought vulnerability was assessed at a 10-km grid scale. Figure 5 shows the spatial distribution of agricultural drought vulnerability in China, and there are apparent east–west and north–south differences. The low- and moderate-vulnerability areas are mainly distributed in the eastern and southern parts of China, while the areas with high and very high vulnerability to agricultural drought are mainly concentrated in the northern and western parts of China.

By integrating the drought vulnerability map with China's agricultural zoning (edited by the committee of China's agricultural encyclopedia, also shown on Fig. 5, we see that the low-vulnerability areas are mainly found in the center of the northwest region, the south of the Huang-Huai-Hai Region, the center of the southwest region, the north of the Middle-Low Reaches of Yangtze River region and the west of South China region, covering 25.2% of the total grain planting area. These areas are mainly described as humid and semi-humid areas, with abundant precipitation, low SCWD, high AWC, and have available irrigation from groundwater or surface water. Previous studies (Li et al. 1996; Fang et al. 1997; Pan et al. 1996; Wang et al. 2002) indicate that even if drought occurs frequently in these

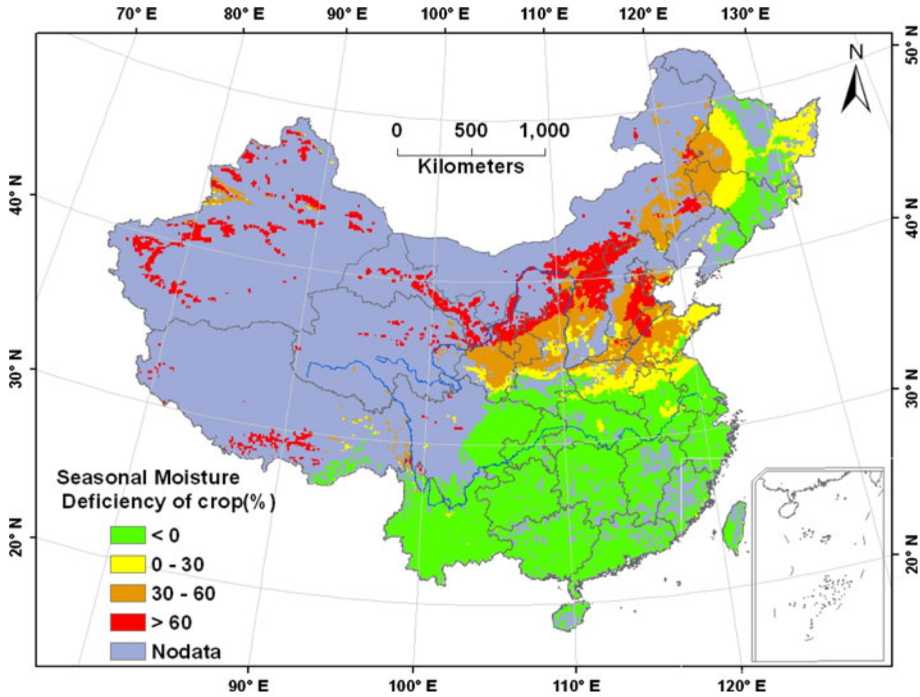

Fig. 4 Spatial variation in seasonal water deficiency of crops in China

low-vulnerability areas, it does not typically result in serious disasters, which means that the reduced vulnerability in these areas effectively reduces the impacts of drought.

The moderate-vulnerability area covers 46.8% of the crop planting area and has the largest area of the four agricultural drought vulnerability levels. It occurs in the west of the northeast region, the north of the Huang-Huai-Hai Region, the north and south of the southwest region, the south of the middle-lower reaches of Yangtze River Region, and the east and west of the South China region. The moderate-vulnerability areas are more seriously affected by agricultural disasters. For example, the Huang-Huai-Hai Region is one of the most serious drought-affected areas in China (Li et al. 1996). In the moderate-vulnerability areas, conditions may be either humid to semi-humid or semi-arid. The humid and semi-humid areas are mainly located in the southwest, middle-lower reaches of Yangtze River, South China and northwest regions. These areas often have low SCWD and high AWC but irrigation is not easily available. For these areas, therefore, effectively reducing drought vulnerability should focus on the construction of water conservation measures to enlarge the irrigation area and enhance the emergency irrigation ability. The semi-arid conditions mainly occur in the Huang-Huai-Hai region, where high water demand crops of winter wheat and corn are common. This type of area is typified by high SCWD, but irrigation by ground water is available, and the AWC in this area is high. However, this area is experiencing a sharp decrease in ground water resources, and therefore reducing vulnerability should depend on not only water-saving irrigation and increasing input but also adjusting planting structures according to the capacity of the water resources under the present socioeconomic conditions and agricultural techniques.

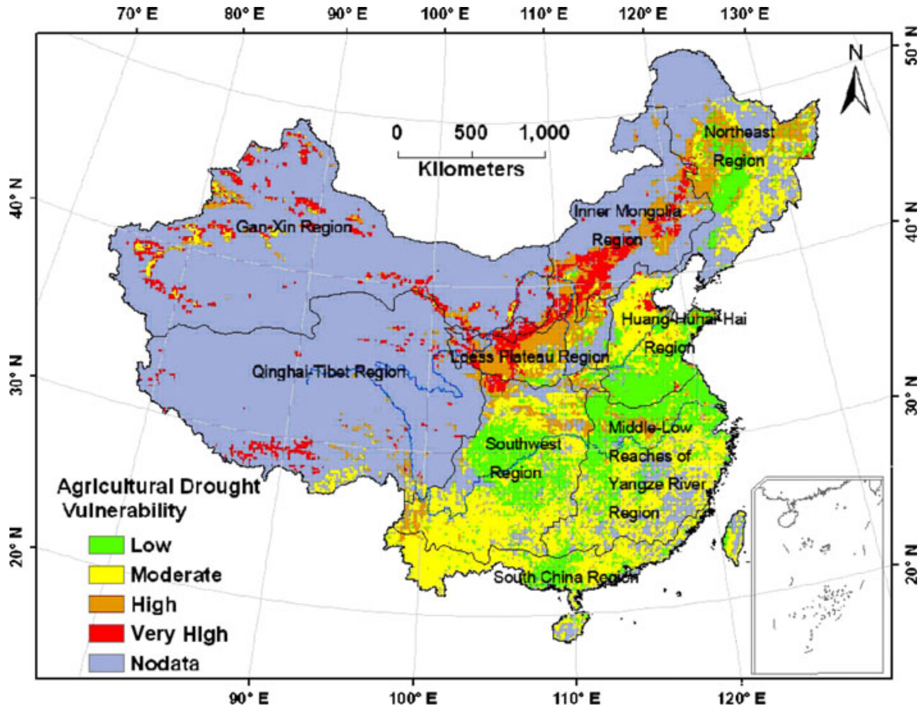

Fig. 5 Spatial variation of agricultural drought vulnerability in China

The high vulnerability areas cover 17.3% of the total crop planting area and are mainly located in the Loess Plateau Region, the northwest and the southeast of the Inner Magnolia Region and small parts of the Gan-Xin and Qinghai-Tibet regions. These areas often are characterized by high or higher SCWD, low AWC and a lower irrigation ratio. The reduction in agricultural drought vulnerability in these areas should depend on both enhancing water conservation and water-saving techniques and also improving the utilization efficiency of water resources. The high vulnerability and frequent occurrences of drought in these areas mean that severe droughts may occur regularly.

The very high vulnerability area covers 10.7% of the crop planting area and mainly occurs in the Inner Mongolia Region, the northwest of the Loess Plateau Region, the southwest of the Qinghai-Tibet Region, and the majority of the Gan-Xin Region. The very high vulnerability of these areas is caused by many natural factors, including a xeric climate, frequent wind, high SCWD, poor soil quality, low AWC, and lack of large-scale irrigation due to water resources scarcity. Reducing vulnerability in this area should rely on inputs of knowledge, technology and financing, especially popularization of water-saving irrigation techniques. At the same time, this area is also a high ecological vulnerability area. To improve eco-environment areas those are not suitable for crop farming should be returned to livestock farming.

The risk of drought hazards mainly depends on variations in the climate conditions that will not change in the short term. Consequently, in high agricultural drought vulnerability areas, to effectively reduce the impacts of drought, the key factors should be identified to understand the mechanisms of vulnerability improve agricultural management and reduce agricultural drought vulnerability.

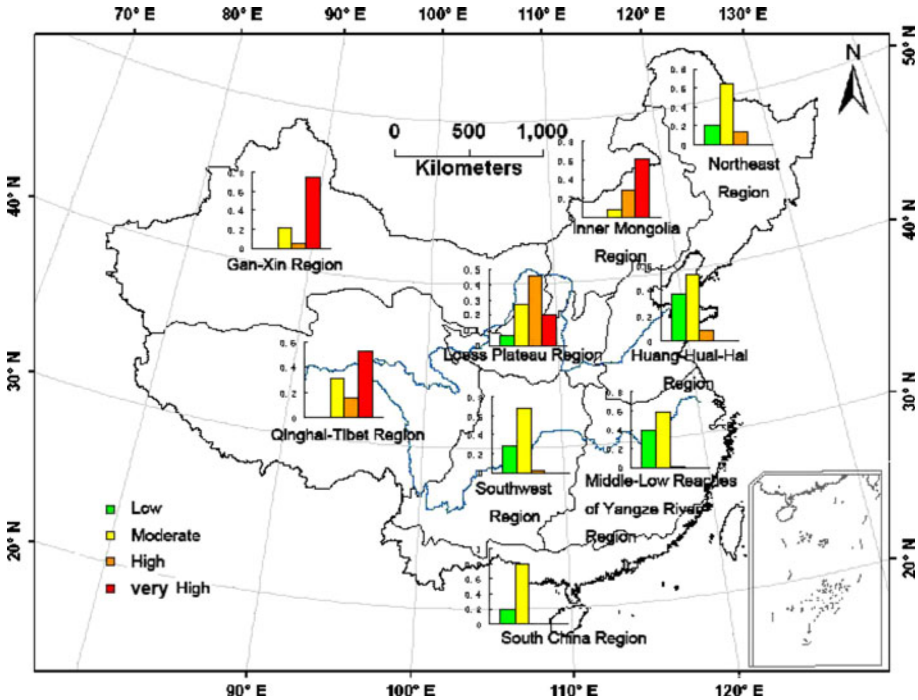

Fig. 6 Regional discrepancy of agricultural drought vulnerability in China

3.3 Analysis of agricultural drought vulnerability in different agriculture regions

As illustrated in Fig. 6 (the area ratio of different agricultural drought vulnerability levels in different agriculture regions), there are variations in the agricultural drought vulnerability between the different agricultural regions. The middle-lower reaches of the Yangtze River, South China, southwest, Huang-Huai-Hai and northeast regions are mainly low and moderate-vulnerability areas. A statistical analysis of the vulnerability factors in different agricultural districts found that the average SCWD in the South China, middle-lower reaches of the Yangtze River and southwest regions are −91.80, −69.10 and −48.80%, respectively. These areas have abundant rainfall, which can meet the needs of crop growth. The average SCWD in the northeast and Huang-Huai-Hai regions are 5.80 and 32.70%, respectively, but the irrigation rate is relatively high, which reduces the vulnerability of agricultural drought to some extent. The irrigation rate in the Huang-Huai-Hai Region is the highest at 88%. In addition, the AWC in all the above regions is relatively high.

Furthermore, within each region, variations in agricultural drought vulnerability are also apparent. For example, the vulnerability in the northern area of middle-lower reaches of the Yangtze River Region is lower than the southern part. Similarly, the eastern part of the northeast region has moderate vulnerability, while the central part has low vulnerability, and the northwest part has high vulnerability. The Huang-Huai-Hai Region shows significant north–south differences, as the southern area has low vulnerability, and the northern area is mainly moderate vulnerability. The low-vulnerability parts of the southwest and South China regions are mainly located in the central areas. The Loess Plateau, Inner Mongolia, Qinghai-Tibet and Gan-Xin regions are areas that have high and very high

Table 3 Area ratio of different agricultural drought vulnerability levels in different agricultural regions and distribution of relative agricultural drought vulnerability factors

Agriculture regions	Area ratio of different vulnerability levels				Seasonal crop water deficiency (%)	Available soil water-holding capacity (mm)	Irrigation area ratio (%)
	Low	Moderate	High	Very high			
Middle-lower reaches of Yangtze River	0.40	0.52	0.07	0.01	−69.10	231.60	42
South China	0.20	0.78	0.02	0.00	−91.80	248.10	20
Southwest	0.29	0.56	0.15	0.00	−48.80	233.30	27
Huang-Huai-Hai	0.38	0.55	0.04	0.03	32.70	243.30	88
Northeast	0.21	0.42	0.36	0.01	5.80	247.20	30
Loess Plateau	0.07	0.18	0.55	0.20	44.50	223.70	25
Inner Mongolia	0.00	0.09	0.29	0.62	61.20	233.70	8
Qinghai-Tibet	0.00	0.26	0.21	0.53	21.23	166.20	1
Gan-Xin	0.00	0.18	0.07	0.75	82.30	181.90	22

agricultural drought vulnerability in China. The high vulnerability area in the Gan-Xin region accounts for 75% of the region's grain production area. The common feature of these areas is the high SCWD values, which in the Gan-Xin Region reaches 82.3%. The soil available water-holding capacity is typically low and is lowest in the Qinghai-Tibet area (166.20 mm). The irrigation rates are also low, at 1 and 8%, for Inner Mongolia and the Qinghai-Tibet Region, respectively. The Loess Plateau has the widest range of agricultural drought vulnerability. The vulnerabilities increase consistently from southeast to northwest (Table 3).

4 Validations

Drought loss is a direct reflection of drought impact on agriculture. Fu Bojie studied the spatial characters of drought in China using agricultural loss data and figured out that the North Plain, the Loess Plateau, the northeast region and the Sichuan basin are the serious drought-affected areas (Fu 1991). Wang Jingai carried out similar study in China and point out that heavy drought area in northern China is relatively concentrated in the western part of Heilongjiang, the central of Inner Mongolia, the north of Hebei, the north of Shaanxi and Ningxia province; in the south are mainly distributed in the central five provinces (Anhui, Hubei, Hunan, Jiangxi and Henan) and the eastern part of Sichuan, Guizhou and Yunnan (Wang et al. 2002). Comparing these results to our study, we find that areas which were seriously affected by drought in the history are mostly located in the high and very high vulnerability areas.

5 Discussion and conclusion

In this study, we assessed overall agricultural drought vulnerability at a 10-km grid scale in China using a GIS-based agricultural drought vulnerability assessment model. The model was constructed by selecting three indicators (climate, soil and irrigation) which contribute to agricultural drought vulnerability. The detailed assessment included analysis of the spatial characteristics of SCWD and agricultural drought vulnerability in China.

The distribution of SCWD in China shows significant differences between the north and south of China, and between the east and west of China. The values for SCWD in the north and west are significantly higher than those in the east and south of China. The SCWD was highly consistent with the aridity/humidity status of the land surface in China.

Due to the variations in agricultural production conditions, obvious differences in agricultural drought vulnerability have been found both within and between different agricultural regions. The spatial distribution of agricultural drought vulnerability in China also shows apparent north–south and east–west differences, with the northern and western parts of China being far more vulnerable to drought than the southern and eastern parts. The areas of crop land with different levels of vulnerability, from low to very high, are 25.2, 46.8, 17.3 and 10.7%, respectively. 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 central part of southwest region, the area from the south of Huang-Huai-Hai region to the north of the middle-lower reaches of the Yangtze region, is the center of the low-vulnerability area in China. The high vulnerability areas are centered in the Loess Plateau, Inner Mongolia and Gan-Xin regions.

At a grid scale, this study constructed a simple model for agricultural drought vulnerability assessment, and using the simple model, we can study agricultural drought vulnerability moving from points to spaces and from small areas to large areas. The conclusions reached in this study could provide essential information to help address the issue of drought vulnerability in China and could also direct drought management strategies for mitigation purposes. Identifying regional vulnerabilities can lead to changing practices in water-dependent sectors and can help decision-makers to incorporate droughts into natural resource planning. For researchers, this study provides a scientific basis for further study of agricultural drought risk assessment.

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References

Allen RG, Pereira LS, Raes D et al (1998) Crop evapotranspiration: guidelines for computing crop water requirement. FAO Irrigation and Drainage, Rome, p 56

Bella S, Nemeth A, Szalai S (2005) Examination of drought vulnerability with GIS tools: Somogyi county case study. Gottinger Geographische Abhandlungen 113:209–217

Blaikie P, Cannon T, Davis I, Wisner B (1994) At risk: natural hazards, people vulnerability, and disasters. Routledge Publisher, London and New York

Chen Y (1995) Main crop water requirement and irrigation of China. Water Resources and Hydropower Press, Beijing

Downing TE, Bakker K (2000) Drought discourse and vulnerability. In: Wilhite DA (ed) Drought: a global assessment, natural hazards and disasters series. Routledge Publishers, UK

Fang X, He Y, Zhang W (1997) An EOF analysis on drought effect on agriculture in China during 1978–1994. J Nat Disasters 6(1):59–64

Fu B (1991) Analysis of the geographical distribution and disastrous condition of drought in China. J Arid Land Resour Environ 5(4):1–7

Gao Z (2006) Development and action of irrigation in China. J Econ Water Resour 24(1):36–39

Hagman G (1984) Prevention better than cure. Report on human and environmental disasters in the third world. Swedish Red Cross, Stockholm. http://soils.usda.gov

Hutchinson MF (1991) The application of thin-plate smoothing splines to continent-wide data assimilation. In: Jasper JD (ed) Data assimilation systems, BMRC Res. report no. 27. Bureau of Meteorology, Melbourne, pp 104–113
IPCC (2001) Climate change 2001: impacts, adaptation and vulnerability of climate change, working group II report. Cambridge University Press, London
Kates RW (1985) The interaction of climate and society. In: Kates RW, Ausubel JH, Berberian M (eds) Climate impact assessment: studies of the interaction of climate and society. Wiley, Chichester
Keenan SP, Krannich RS (1997) The social context of perceived drought vulnerability. Rural Sociol 62:69–88
Kern JS (1995) Geographic patterns of soil water-holding capacity in the contiguous United States. Soil Sci Soc Amer 59:1126–1133
Klocke NL, Hergert GW (1990) How soil holds water, new guide G90-964, INAR. University of Nebraska, Lincoln
Knutson C, Hayes M, Phillips T (1998) How to reduce drought risk, western drought coordination council preparedness and mitigation group
Lei Z, Luo Y, Yang S, Shi X et al (1999) Calculation of crop coefficient with meteorological data. Tran Chin Soc Agric Eng 15(3):119–122
Li K, Yin S, Sha W (1996) Characters of time-space of recent drought in China. Geogr Res 15(3):6–15
Liu H, Kang Y (2006) Calculation of crop coefficient of winter wheat at elongation-heading stages. Trans Chin J Agric Eng 22(10):52–56
Liu Y, Pereira LS (2000) Validation of FAO methods for estimating crop coefficients. Tran Chin Soc Agric Eng 16(5):26–30
Liu C, Zhang X, You M (1998) Determination of daily evaporation and evapotranspiration of winter wheat field by large scale weighing lysimeter and micro lysimeter. J Hydraulic Eng 10:36–39
Liu L, Liu S, Liu P et al (2002) Synthetic analysis and quantitative estimation of the agricultural vulnerability to drought disaster in Hunan Province. J Nat Disasters 11(4):78–83
Liu M, Tang X, Zhuang D (2003) A new technique on spatial-temporal data fusion and construction of grid data platform. Geo-Inf Sci 4:63–68
Liu LF, Guan X, Tang Y-S (2005) Vulnerability of agricultural drought and agricultural losses reduction during drought through implementation of ecological measures—A case study of Hengyang, Hu-nan Province. Bull Soil Water Conserv 25(2):69–73
Marshall TJ (1979) Soil physics. Cambridge University Press, Cambridge
NCAR (2005) Drought's growing reach: NCAR study points to global warming as key factor. http://www.ucar.edu/news/releases/2005/drought_research.shtml
Pan Y, Gong D, Wang P (1996) A research on temporal-spatial characteristics of drought in China during 1949–1990. J Beijing Norm Univ 32(1):138–143
Peng S, Ding J, Mao Z (2007) Estimation and verification of crop coefficient for water saving irrigation of late rice using the FAO-56 method. Trans Chin Soc Agric Eng 23(7):30–34
Ribot JC, Najam A, Watson G (1996) Climate variation, vulnerability and sustainable development in the semi-arid tropics. In: Ribot JC, Magalhães AR, Panagides SS (eds) Climate variability, climate change and social vulnerability in the semi-arid tropics. Cambridge University Press, New York, pp 13–51
Scotter DR (1981) Field capacity of water and soil available water. Soil Sci Am 45(5):852–855
Shahid S, Behrawan H (2007) Drought risk assessment in the west part of Bangladesh. Nat Hazards 46:391–413
Shang Y (1999) Agricultural drought disaster vulnerability assessment and the establishment of the correlation. J Hebei Norm Univ 23(3):420–428
Shang Y (2000a) Causes analysis of the changes of agricultural drought disaster vulnerability in Hebei Province. J Nat Disasters 9(1):40–46
Shang Y (2000b) The analysis of drought, agricultural drought disaster and the farmhouses vulnerability: taking the typical farmhouses of Xingtai County as an example. J Nat Disasters 9(2):55–61
Shang Y, Shi P (1998) Discussion on the role of anthropogenic factors in the forming of agricultural drought disaster process. J Nat Disasters 7(4):35–43
Shang Y, Huang D, Yang J (2006) Diagnosis and assessment of agricultural drought system's vulnerability in irrigated area—taking Xingtai County of Hebei Province as an example. Areal Res Dev 25(5):117–121
Smith RM (1986) Comparing traditional methods for selecting class intervals on choropleth maps. Prof Geogr 38(1):62–67
Su Y, Li L, Wu Z-Z et al (2005) Analysis of hazard-affected body s vulnerability in formative process of agricultural drought: a case study on Dingcheng district in Hunan. J Nat Disasters 14(6):83–87

Sun J, Liu Z, Zhang J et al (2002) Crop coefficients of spring wheat in Windy dust area. Trans Chin Soc Agric Eng 18(6):55–58
Wang Y (1981) Affect of altitude to the two factors ($\delta/((\delta+\gamma)$ and $\gamma/((\delta+\gamma)$ in Penman formula. Acta Meteorol Sin 39(4):503–506 (in Chinese)
Wang L, Chen S, Hou G (1988) Revision of Penman formula by altitude to calculate potential evapotranspiration. Acta Meteorol Sini 46(3):381–383 (in Chinese)
Wang J, Sun H, Xu W (2002) Spatio temporal change of drought disaster in China in recent 50 years. J Nat Disasters 11(2):1–6
Wang J, Shang Y, Su Y et al (2005a) A vulnerability diagnosis of agricultural drought disasters and regional sustainable development in China. J Beijing Norm Univ 3:031–731 (Social Science Edition)
Wang X, Liang W, Wen D (2005b) Analysis of paddy field evapotranspiration in North China and calculation of crop coefficient. Chin J Appl Ecol 16(1):69–72
Wang J, Su Y, Shang Y (2006) Vulnerability identification and assessment of agriculture drought disaster in China. Adv Earth Sci 21(2):161–168
Wilhelmi OV, Wilhite DA (2002) Assessing vulnerability to agricultural drought: a Nebraska case study. Nat Hazards 25:37–58
Wilhite DA (1993) The enigma of drought, chapter 1. In: Wilhite DA (ed) Drought assessment, management, and planning: theory and case studies. Kluwer Academic Publishers, Boston, MA, pp 3–17
Wilhite DA (2000) Drought as a natural hazard: concepts and definitions, chapter 1. In: Wilhite DA (ed) Drought: a global assessment, natural hazards and disasters series. Routledge Publishers, UK
Wu S, Yin Y, Zheng D et al (2005) Aridity/humidity status of land surface in China during the last three decades. Sci China Ser D Earth Sci 48(9):1510–1518
Yang X, Bouman BAM, Zhang Q et al (2006) Crop coefficient of aerobic rice in North China. Trans Chin Soc Agric Eng 22(2):37–41
Yin Y, Wu S, Zheng D et al (2005) Regional difference of aridity/humidity conditions changeover China during the last thirty years. Chin Sci Bull 50(19):2226–2233
Zhang F, Wang D, Qiu B (1987) China's agricultural phrenology Atlas. Science Press, Beijing
Zhang X, Chen S, Pei D et al (2002) Evapotranspiration, yield and crop coefficient of irrigated maize under straw mulch conditions. Prog Geogr 21(6):583–592
Zuo D, Yixian W, Jiansui C (1993) Spatial distribution characteristics of solar radiation in China, Zuo Dakang's geographical research papers in Chinese. Science Press, Beijing, pp 168–185