

Research papers

Effects of meteorological droughts on agricultural water resources in southern China

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ABSTRACT

With the global warming, frequencies of drought are rising in the humid area of southern China. In this study, the effects of meteorological drought on the agricultural water resource based on the agricultural water resource carrying capacity (AWRCC) in southern China were investigated. The entire study area was divided into three regions based on the distributions of climate and agriculture. The concept of the maximum available water resources for crops was used to calculate AWRCC. Meanwhile, an agricultural drought intensity index (ADI), which was suitable for rice planting areas, was proposed based on the difference between crop water requirements and precipitation. The actual drought area and crop yield in drought years from 1961 to 2010 were analyzed. The results showed that ADI and AWRCC were significantly correlated with the actual drought occurrence area and food yield in the study area, which indicated ADI and AWRCC could be used in drought-related studies. The effects of seasonal droughts on AWRCC strongly depended on both the crop growth season and planting structure. The influence of meteorological drought on agricultural water resources was pronounced in regions with abundant water resources, especially in Southwest China, which was the most vulnerable to droughts. In Southwest China, which has dry and wet seasons, reducing the planting area of dry season crops and rice could improve AWRCC during drought years. Likewise, reducing the planting area of double-season rice could improve AWRCC during drought years in regions with a double-season rice cropping system. Our findings highlight the importance of adjusting the proportions of crop planting to improve the utilization efficiency of agricultural water resources and alleviate drought hazards in some humid areas.

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1. Introduction

Climate warming and increased climate variability have led to a greater number of drought events in many river basins around the globe, particularly at intermediate and high latitudes (Mishra et al., 2009; IPCC, 2013; Zhao et al., 2016). Climate change has increased the frequency of droughts (Gleick, 1987; Karl and Riebsame, 1989; Lettenmaier and Gann, 1990; Panagoulia, 1992; Vimal et al., 2010). Moreover, future climate change may lead to more frequent and severe droughts (Quiring, 2015). Droughts are now a major threat to crop production in many areas of the world. In recent years, droughts have been a focus of study for environmentalists, ecologists, hydrologists, meteorologists and agricultural scientists (Wilhite, 2000; Bola et al., 2014; Zhao et al., 2016).

Agriculture, which strongly depends on water resources, will be affected by climate change and increasing drought frequency. Droughts are caused by a precipitation deficiency. Studying the effects of droughts on the carrying capacity is important to optimize crop management and agricultural planning. The term “carrying capacity” has been used since the late 1880s (Seidl et al., 1999) and was clearly defined by Park and Ernest (1921). Carrying capacity has been typically defined as the maximum population size that can be supported indefinitely by a given environment. This concept has since been widely used in many fields. Meadows et al. (1972) built a model of the world for economy growth by using the concept of carrying capacity. This research was the first indirect study of water resource carrying capacity. Harris and Scott (1999) studied agricultural production and regional agricultural water resource carrying capacity. These authors investigated the yield growth patterns of major cereal crops, soil degradation, water overdraft, and other ecosystem stressors and concluded that the

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world was close to its agricultural carrying capacity and that specific resource and ecological constraints were very importance at the regional level. Many studies on water resource carrying capacity have been incorporated into strategies for sustainable development. The definition of water resource carrying capacity varies (Hixon, 2008). In this study, the agricultural water resource carrying capacity (AWRCC) is defined as the maximum crop production that a regional water resource can support without environmental degradation. If deficits in precipitation and soil moisture continue, these phenomena can reduce AWRCC. When agricultural water needs are not met by precipitation, AWRCC will be overloaded without changes in agricultural structure or the introduction of blue water with water (Falkenmark, 1995). Although irrigation is an effective way to reduce agricultural drought, research of Leng et al. (2015a) showed that irrigation would increase vulnerability to drought, and the combined effect of increased irrigation water demand and amplified temporal-spatial variability of water supply may lead to severe local water scarcity for irrigation. Therefore, the role of adjustment of agricultural planting structures for increasing AWRCC to adapt to climate change needs investigation.

Southern China, located in the humid subtropical climate zone (Peel et al., 2007), is an important agricultural region. Water resources are relatively abundant here, but seasonal droughts can drastically affect crop growth (Xu et al., 2012) and dramatically affect the AWRCC. Climate warming is projected to continue along with more frequent droughts in China (Gao et al., 2012). In the future, agricultural drought in southern China tends to increase with severe intensity, longer duration and higher frequency (Leng et al., 2015b). Southern China is especially at risk (Chen et al., 2013) for two major reasons. First, Global Climate Models generally indicate that precipitation will decrease at low and mid-latitudes and will be less than evapotranspiration in mid-continent regions. Therefore, more severe, longer-lasting droughts may occur in these areas. Second, the temperatures in southern China are now at the upper limit of the optimal temperature for plant growth, whereas the temperatures in other regions of China are at the middle point of the optimal temperature for plant growth, which provides more buffer space. Therefore, continued global warming may induce more detrimental effects on crops in southern China than on crops in other regions.

Huang and Yang et al. (2010) studied the evolutionary characteristics of seasonal droughts in southern China during the past

58 years based on a standardized precipitation index. Huang (2011) evaluated the characteristics and causes of droughts in China from 1949 to 2007. Fang et al. (2011) studied the trends and distributive characteristics of agrometeorological disasters in China over the past 30 years. Sui et al. (2012a, 2012b) documented changes in precipitation and the spatiotemporal characteristics of droughts for wintering grain and oil crops in southern China based on a crop water deficit index. Consequently, the need for drought assessment is crucial to minimize socio-economic losses. To date, however, the potential effects of meteorological droughts on the agricultural water resources in the humid regions of southern China have not been uniformly evaluated.

This study was designed to 1) establish the agricultural drought intensity index (ADI), which was suitable for rice planting areas for agricultural drought evaluation in southern China; 2) investigate the effects of meteorological droughts on the agricultural water resource carrying capacity (AWRCC) in different regions in southern China from 1961 to 2010; 3) explore the effects of meteorological droughts on agricultural water resource in southern China; and 4) present countermeasures for drought prevention and provide a scientific basis for sustainable agricultural production in southern China to adapt to future climate change.

2. Materials and methods

2.1. Study area

The southern China study area is located between 20–30° N and 100–120° E (Fig. 1). This area has a warm temperate climate with hot summers (climate type C, temperature type a, Koppen-Geiger climate classification; Kottek et al. 2006). The seasonal distribution of precipitation differs in the eastern and western portions. The eastern portion is mainly affected by the East Asian summer monsoon, which originates from the Pacific Ocean, while the western portion is mainly affected by the South Asian monsoon, which originates in the Indian Ocean. The South Asian monsoon begins significantly later than the East Asian monsoon. The most obvious characteristic of a monsoon climate is the simultaneous rainy and hot season. Winter and summer have distinctive climate characteristics. Monsoon climates are conducive to good crop growth and high yields, but monsoon climates can vary greatly. The onset of the summer monsoon determines the length of the rainy season,

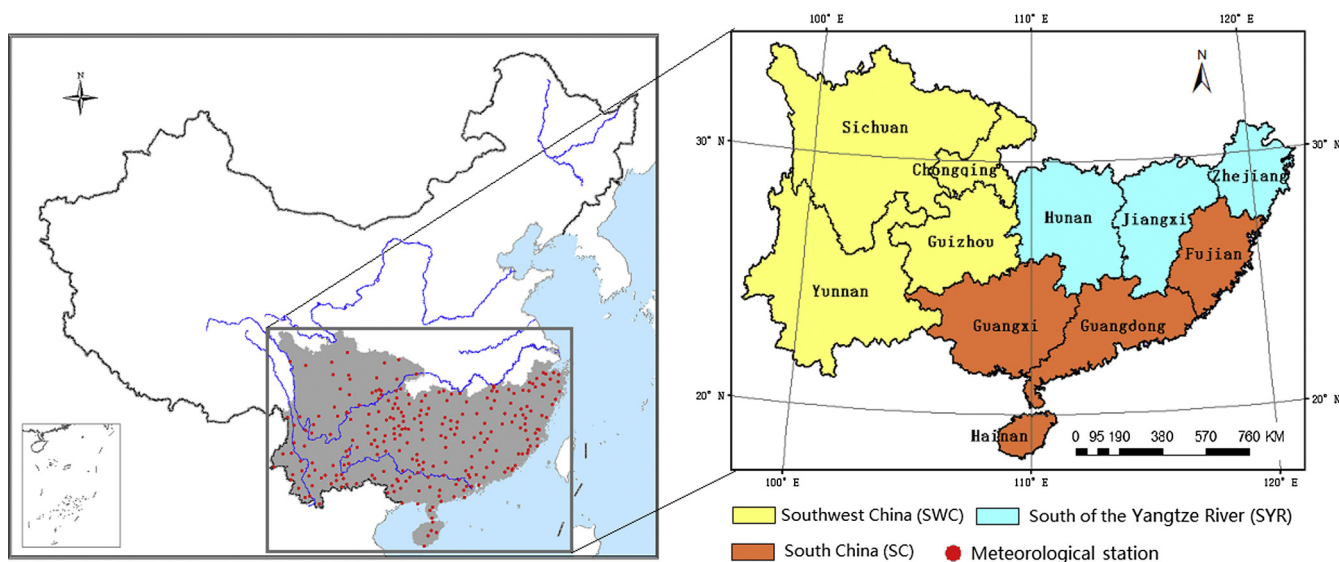


Fig. 1. Study area, distribution of meteorological stations and the three sub-regions of southern China.

which can lead to either droughts or floods, with consequent agricultural losses.

The eastern portion can be further divided into two regions based on the different timings of major summer monsoon rainfall. Monsoon rainfall mainly occurs during April and May in the southern part and during June and July in the northern part. In this study, the southern part is termed the South China (SC) and the northern part is referred to as the South of the Yangtze River (SYR). The western portion of the study area is called the Southwest China (SWC) (Fig. 1). The SC region consists of the Fujian, Guangdong, Guangxi and Hainan coastal provinces. The SYR region covers the Zhejiang, Jiangxi, and Hunan provinces. The SWC region includes the Yunnan, Sichuan, and Guizhou provinces and Chongqing City. The terrain is relatively flat, mixed with plains and hills in SC and SYR, but is very complex in SWC, which contains the Sichuan Basin, Yungui Plateau, and West Sichuan plateau. Agriculture in SWC mainly occurs in the Sichuan Basin and surrounding uplands.

Regional crop pattern differences are significant because of the diversity in the climate, soil, and dietary patterns among these regions in China. In southern China, the most important crop is rice (Wang et al., 2014). Although sequential cropping systems are used in all three regions, the crop species and their growing seasons differ in each region. In SC and SYR, growing two rice crops is common in paddy landscapes. Early rice is planted from February to April and harvested in June and July. Late rice is planted immediately after the early rice harvest. The major crops in SWC are winter wheat and middle season rice. Winter wheat is grown from November to the following April. The middle-season rice growing season lasts from May to September. The water demand at each crop growth stage is different. Monsoon rainfall variability and seasonal droughts have different effects on the crops within the three regions (Huang, 2004), so improving our understanding of these seasonal droughts and their effects on crops is important.

2.2. Data

The data used in this study include meteorological observations and agricultural statistics. In order to investigate the interannual climate variability, 50 years of continuous data from 256 meteorological stations in the study area were selected. These stations are located in the main agricultural areas. Daily meteorological data were from 1961 to 2010. The variables included the temperature, precipitation, water vapour pressure, wind speed and sunshine hours.

Agricultural data were collected from the National Bureau of Statistics of China. The data include the planting area, drought area, and crop yields. Data for drought-affected areas and crop yields were available only for the years 1978–2010, while data for the other variables were available from 1961 to 2010.

2.3. Methods

The main effect of meteorological droughts on agriculture is the reduction of available agricultural water resources, which causes crop water stress and decreases the yield. We used anomalous agricultural water budgets and the actual drought area as the drought index and the crop yield from water consumption as the water carrying capacity index to analyze the effects of meteorological droughts on AWRCC and agriculture.

2.3.1. Agricultural drought indices

Agricultural droughts are a deficiency in water availability for crop or plant growth, as defined by the UNCCD (2003). Several drought indices have been developed to quantitatively evaluate

drought intensity. The most common is the Palmer Drought Severity Index (PDSI) (Palmer, 1965). The PDSI was the first drought indicator to comprehensively assess moisture status. This index primarily reflects long-term drought. The Crop Moisture Index (CMI) reflects short-term moisture supply across major crop-producing regions and identifies potential short-term agricultural droughts. Huang et al. (2015) applied the variable fuzzy set theory to develop an Integrated Drought Index (IDI) combining meteorological, hydrological, and agricultural factors across the Yellow River basin in North China. The Integrated Drought Index (IDI) has a better performance compared with Standardized Precipitation Index (SPI) and Standardized stream flow Index (SSFI), and it is more sensitive and effective to capture drought onset and persistence. However, drought indices that are related to soil moisture are inappropriate in humid regions where paddy rice is the main crop. Therefore, three alternative drought indices were defined based on statistical data in this study, which are drought hazard rate and extent index, and agricultural drought intensity index based on meteorological environment and crop water demand.

(a) Drought hazard rate

The drought hazard rate (DHR) is defined as the ratio of the crop planting area affected by droughts (A_{da}) to the crop planting area covered by droughts (A_{dc}), where the crop planting area affected by droughts is the area in which crop yield is reduced over 30% by droughts and the crop planting area covered by droughts is the area in which the crop yield is reduced over 10% by droughts (Yan et al., 2009) in the same year. DHR is given by

$$DHR = \frac{A_{da}}{A_{dc}} \times 100\% \quad (1)$$

Both A_{da} and A_{dc} were from the Chinese Statistical Bureau. The DHR can be used to describe the degree of actual damage from droughts.

(b) Drought Extent index (DEI)

The drought extent index (DEI) is defined as the ratio of A_{dc} divided by the crop planting area A_s in the same year:

$$DEI = \frac{A_{dc}}{A_s} \times 100\% \quad (2)$$

A_s was also from the Chinese Statistical Bureau. DEI can be used to describe the actual intensity of droughts.

Both DHR and DEI are based on statistical data. However, A_{da} , A_{dc} and A_s are not available before 1978 or for the current year, while meteorological data are available from 1961.

(c) Agricultural drought intensity index (ADI)

Agricultural drought intensity index (ADI) is defined as

$$ADI = \Delta WB_r = \left(\frac{WB_r - \overline{WB_r}}{\overline{WB_r}} \right) \times 100\% \quad (3)$$

where $WB_r = \frac{P-ET_0}{ET_0}$ is the relative difference between the water supply from precipitation (P) and the crop water demand or requirement as measured by evapotranspiration (ET_0). $\overline{WB_r}$ is the average of WB_r over the period from 1961 to 2010. ET_0 was estimated by the FAO Penman-Monteith equation (Allen et al., 1998).

ADI reflects the degree to which water requirements are met. A large negative ADI indicates a local water deficit and an inability to meet water demands for normal crop growth and development. ADI can be divided into four levels: (1) no drought ($ADI \geq -20$); (2) mild drought with no obvious crop effects ($-20 > ADI \geq -45$);

(3) moderate drought that produces some crop damage ($-45 > ADI \geq -70$); and (4) severe drought that reduces crop yield ($ADI < -70$).

2.3.2. Agricultural water resource carrying capacity (AWRCC)

Water resources can be divided into blue water and green water (Falkenmark and Rockström, 2006). Blue water refers to the water in surface water bodies and groundwater, while green water is essentially rainfall that (after infiltration into the unsaturated soil zone) is directly used by plants to produce biomass (Falkenmark and Rockström, 2006; Liu and Savenije, 2008; Savenije, 2000). Crop production mainly relies on green water. In this study, the precipitation during the growth season was used to evaluate AWRCC. Many factors affect AWRCC, including the climate, non-agricultural water use, crop varieties, fertilizer applications, etc. Only the climate conditions (drought) and plant type were considered in this study. Three indices were calculated for AWRCC: the water resource carrying capacity for a single crop (WRCCC) in a region, the water resource carrying capacity for all crops in a region (WRCCR) and the anomaly of the water resource carrying capacity (AWRC) for the WRCCC and WRCCR.

2.3.2.1. WRCCC. WRCCC measures the green water resources during the growth season that could produce the maximum yield of crops under the current cropping patterns. This index indicates the potential water productivity under limited agricultural water resources. WRCCC is calculated based on the Jensen model (Jensen, 1968):

$$WRCCC_j = P_j \times CWP_j \times \prod_{i=1}^I \left(\frac{ET_{pi}}{ET_{pmi}} \right)^{\lambda_i} \quad (4)$$

where the subscripts i and j are the crop growth stage and crop type, respectively, and the letters i are the corresponding total number of growth stages of crop j . $WRCCC_j$ is the water carrying capacity of crop j , and P_j is the total precipitation (m) in the growth season of crop j , which represents the largest green water resource. CWP_j is the agricultural water productivity (kg m^{-3}) of crop j . The value of CWP for each crop was taken from data by Huang and Li (2010a). ET_{pi} and ET_{pmi} are the actual and maximum crop evapotranspiration (m) in growth stage i , respectively, and are calculated according to the FAO Irrigation and Drainage Paper No. 56 (Allen et al., 1998). λ is a water sensitive index at the growth stage i of a crop, which reflects the influence of water stress during a growth stage of a crop on the yield. The values of λ and ET_{pm} were from Xiao et al. (2008) and Tao (1998).

2.3.2.2. WRCCR. WRCCR is the maximum agricultural production that is supported by the current water resources under the current technical, economic and social conditions. Regional agricultural water resources could carry the largest crop planting area under the specific regional climate, which is a constant or slightly varying value. WRCCR is the sum of WRCCCs for all the crops in a region:

$$WRCCR = \sum_{j=1}^J Q_j \times WRCCC_j \quad (5)$$

where $Q_j \frac{A_j}{A}$ is the weighting factor of crop j , A_j is the acreage (hm^2) of crop j , and A is the acreage (hm^2) of all the food crops.

2.3.2.3. Anomaly of the water resource carrying capacity. The anomaly of the water resource carrying capacity (AWRC) is used to measure the influence of droughts on water resources. AWRC is calculated as follows:

$$AWRC_i = \frac{WRC_i - \overline{WRC}}{\overline{WRC}} \times 100\% \quad (6)$$

where $AWRC_i$ is the deviation in the water resource carrying capacity in year i (%). WRC_i is $WRCCC_i$ or $WRCCR_i$ in year i . $\overline{WRC}$ is the average of $WRCCC_i$ or $WRCCR_i$ from 1961 to 2010.

2.3.3. Meteorological yield of crop (MY)

Crop yield is affected by many factors, among which the agricultural technology and weather conditions are two significant ones. The development of agricultural technology is a steady and gradual process, while weather conditions have remarkable inter-annual and inter-decadal variations. Agricultural technology is developed to enhance crop production and increase crop yield, while weather conditions can cause significant fluctuations in crop yields from year to year. Therefore, the crop yield can be divided into two parts: the time trend yield (TY), which is related to the effect of agricultural technology on crop production, and the meteorological yield (MY), which is related to the effects of weather conditions on crop growth and developments. The time trend yield always increases over time, while the meteorological yield can be positive or negative at different times. However, crop yield variations that are short-lived are not necessarily related to environmental conditions. Before the effect of weather conditions can be assessed, it is necessary to remove the trend (that is, to “detrend” the time series) and other non-weather factors. Several detrend methods exist to separate these two factors (World Meteorological Organization, 2010). In this study, the methods of linear and quadratic regression, the moving average over seven, five, three consecutive years and the difference between the two adjacent years were used to fit trend yield. We found that the method of moving average over three consecutive years was the best for different regions and all crops. Therefore it was used to get the time trend yield. The meteorological yield is the difference between the actual yield and the time trend yield, which was also used in other drought assessments (Larissa et al., 2015). Positive MY values indicate that the

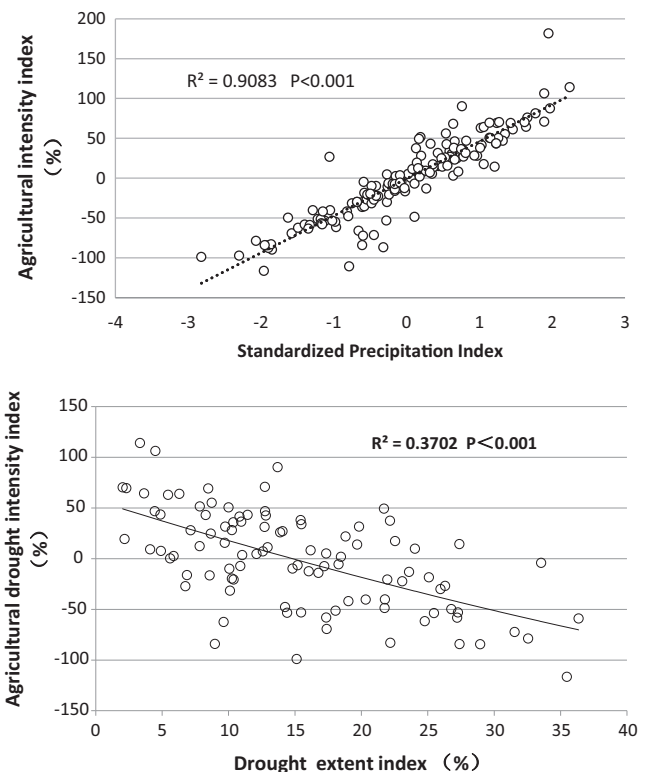


Fig. 2. Relationships between ADI, SPI and DEI for the study area from 1978 to 2010. Top panel – ADI vs SPI; Bottom panel – ADI vs DEI.

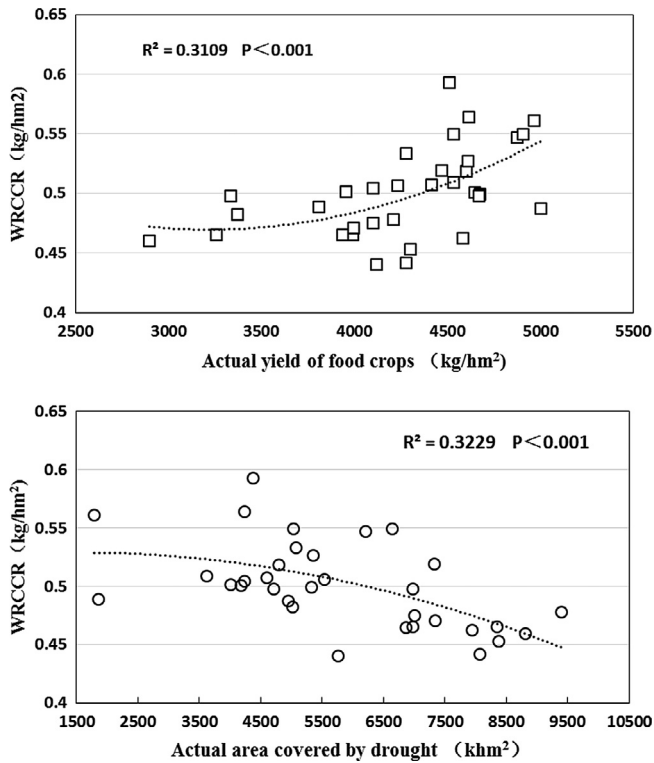


Fig. 3. Relationships between the WRCCR and average yield of food crops (top) and the total area covered by drought (bottom) for the study area from 1978 to 2010.

weather conditions are favorable for crop production, while negative MY values indicate that the weather conditions are unfavorable for crop production. The MY was used to estimate the effects of droughts on crops during typical drought years:

$$MY_i = \frac{y_i - y_{ti}}{y_{ti}} \times 100\% \quad (7)$$

where MY_i represents the meteorological yield of a crop in the year i (%). y_i and y_{ti} are the actual crop yield and the trend yield of a crop in the year i (kg/hm²), respectively.

3. Results

3.1. Verifications of the ADI and WRCCC

Meteorological drought is the basis of agricultural drought. The Standardized Precipitation Index (SPI) (Hayes et al., 1999) is a traditional meteorological drought index. By comparing SPI and ADI in three regions, we found that the correlation between SPI and ADI was very significant, which indicated that ADI was consistent with the meteorological drought index in drought intensity (Fig. 2). The reliability of ADI was also verified by DEI in three regions from 1978 to 2010. The results indicate that ADI was significantly related to DEI for the study region ($P < 0.1\%$), which proves that ADI could be used to identify droughts (Fig. 2).

We examined the correlation among the average yields of food crops, the total area covered by drought and WRCCR in the study area from 1978 to 2010 to test the suitability of AWRCC. The results (Fig. 3) showed that WRCCR had a good correlation ($P < 0.1\%$) with both the food crops yield and the drought area. This figure showed

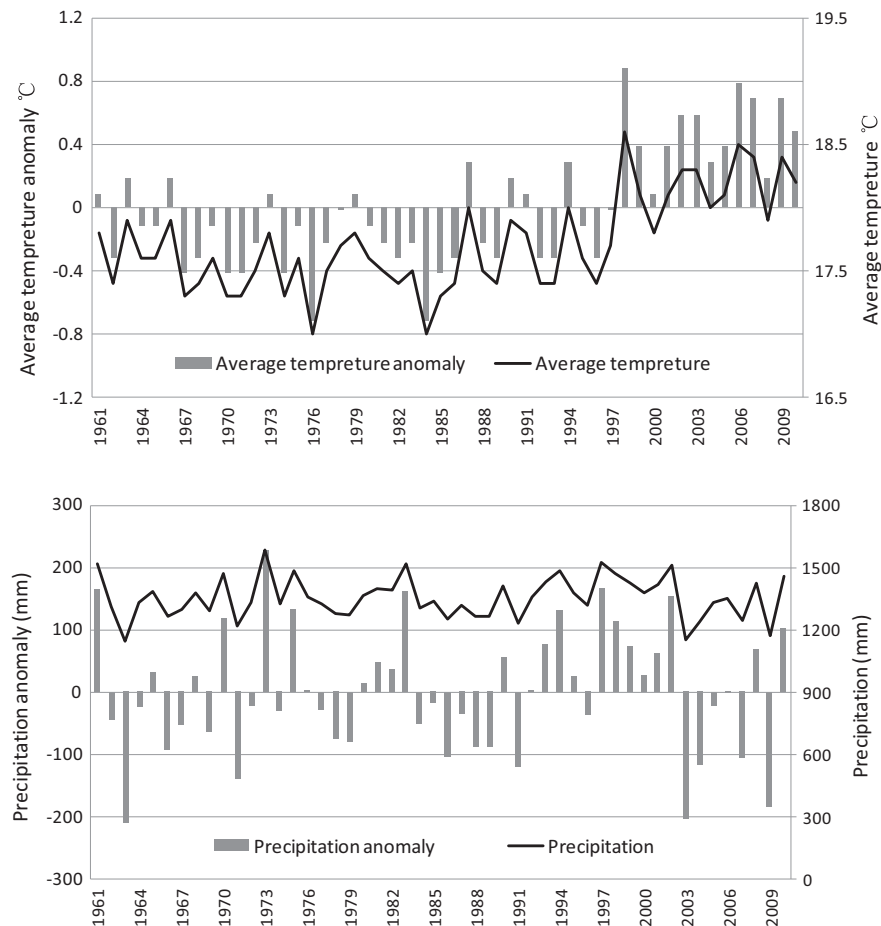


Fig. 4. Time series of the temperature (top) and precipitation (bottom) averaged over the study area and their anomalies from 1961 to 2010.

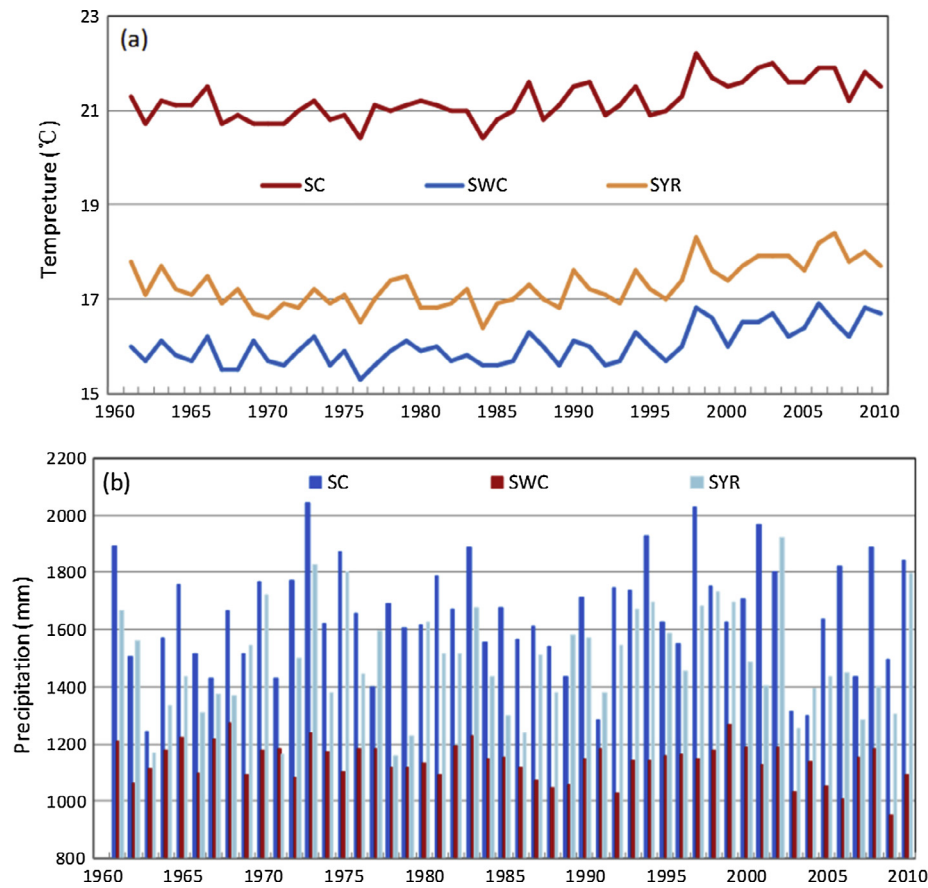


Fig. 5. Time series of the temperature (a) and precipitation (b) for the three regions from 1961 to 2010.

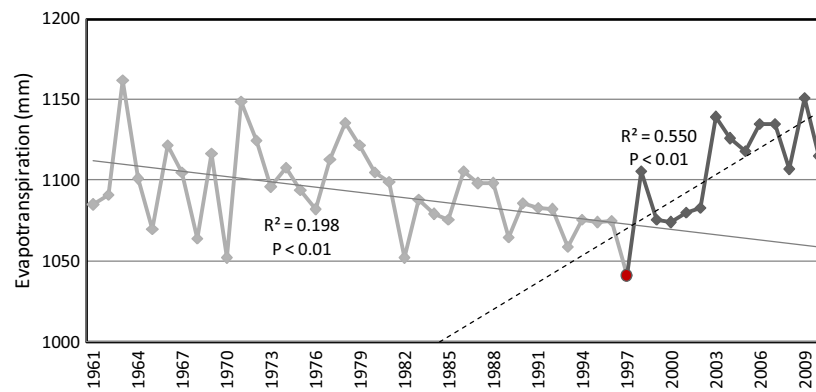


Fig. 6. Time series of the average evapotranspiration over the study area from 1961 to 2010.

that WRCCR reflects both the water production capacity and the drought situation in the study area. Thus, WRCCR could be used to evaluate the effects of droughts on agriculture.

3.2. Variations in climate, agricultural drought and water resource carrying capacity in southern China

3.2.1. Climate

The annual mean temperature for the entire study area changed during the early 1980s from slight decreasing to large increasing trends (Fig. 4). The increasing trends became much more substantial after 1997 at a rate of 0.5 °C per year. In contrast, the annual mean precipitation (Fig. 4) was characterized by large inter-annual

variability, a feature that was consistent with other studies (Wang et al., 2001; Gong and Ho, 2002; Wang et al., 2013). However, a large decreasing trend was observed from the early 1990s.

Substantial differences existed in the magnitudes of the temperature and precipitation among the three regions (Fig. 5). The temperature was the highest in SC (21–22 °C), with much lower values in the other two regions (Fig. 5a). The lowest was in SWC (approximately 16 °C). The annual mean precipitation and its inter-annual variability were much larger in SC and SYR than in SWC (Fig. 5b).

The annual mean evapotranspiration over the entire study area declined until 1997, then remarkably increased at a rate of approximately 5 mm/m² per year (Fig. 6). The increasing trend after 1997

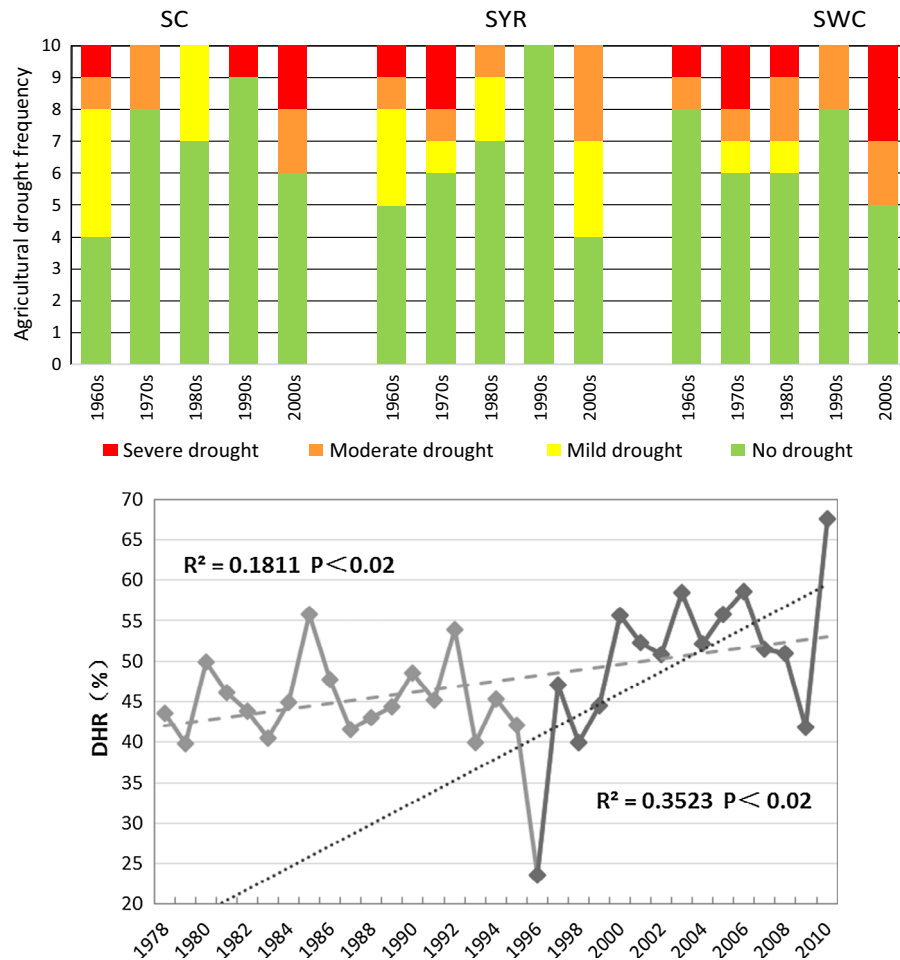


Fig. 7. Decadal frequency of agricultural droughts at different grades in the three regions (top) and DHR time variation in the study area during 1978 and 2010.

appeared to be consistent with the large increasing trend of temperature. Evapotranspiration is an important component of the hydrologic cycle, and affects water availability and agriculture (Burn and Hesch, 2007). The remarkable increase in evapotranspiration and the large decrease in precipitation after 1997 resulted in more frequent agricultural drought events.

3.2.2. Agricultural droughts

The decadal drought frequency and intensity for the three regions were calculated based on ADI and are shown in Fig. 7. Among the three regions, SWC region had 17 droughts, SC region had 16 droughts, and SYR region had 18 droughts during the period between 1961 and 2010. Although the number of droughts in the three regions was almost same during these 50 years, SWC had more moderate and severe droughts, where average of EDI during 1978 and 2010 was 16% higher than other regions. SC region had 7 mild droughts, 5 moderate droughts and 4 severe droughts. Three mild droughts occurred in the 1980s. Droughts occurred more frequently in the 2000s, including 2 severe droughts, 2 moderate droughts and 1 mild drought. The averages of EDI and HDR in SC were 14% and 34% in the 1980s, 14% and 46% in the 1990s, 15% and 50% in the 2000s, respectively. In SYR region, droughts occurred 50% of the time during the 1960s, including 3 mild, 1 moderate and 1 severe drought. The intensity of the droughts during the 1970s was stronger than that during the 1980s, with two severe droughts. Droughts became much less frequent from the 1980s to 1990s. The frequency was zero in the 1990s, and the drought intensity during these 2 decades was significantly less

than that during the 1960s and 1970s. Droughts clearly increased in frequency in the 2000s. In this region, the averaged EDI in the 1990s was 13% which is lower than that in the 1980s by three percentage points, and the averaged HDR in the 1990s was 41% lower than that in the 2000s by fifteen percentage points. In SWC, droughts occurred 40% of the time from the 1970s to the 1980s, reduced to 20% during the 1990s, and then increased to 50% during the 2000s. The drought intensity also intensified during the 2000s, when the averaged EDI and HDR were 17% and 52%, respectively. The frequency of moderate and severe droughts obviously increased during the 2000s in all three regions (Fig. 7). Meanwhile, the variation of actual occurrence of droughts showed that the DHR clearly increased, especially since the late 1990s, which was consistent with the evapotranspiration trend (Fig. 6, Fig. 7). This result implies that droughts intensified and agricultural losses increased to an extreme degree in the area that was covered by drought.

The spatial distribution of the mild, moderate and severe droughts during this 50-year period for the entire study region is shown in Fig. 8. The eastern part of the study region had a higher amount of mild and moderate droughts and fewer severe droughts, while the western part had more severe droughts but fewer mild and moderate droughts. This was consistent with Fig. 7, where the frequency of severe drought was higher in SWC region than that in other regions. Severe droughts were more localized than mild and moderate droughts: some small areas, such as the southern corner of Sichuan Province and the southwestern Guanxi Province, had more severe droughts than the entire region.

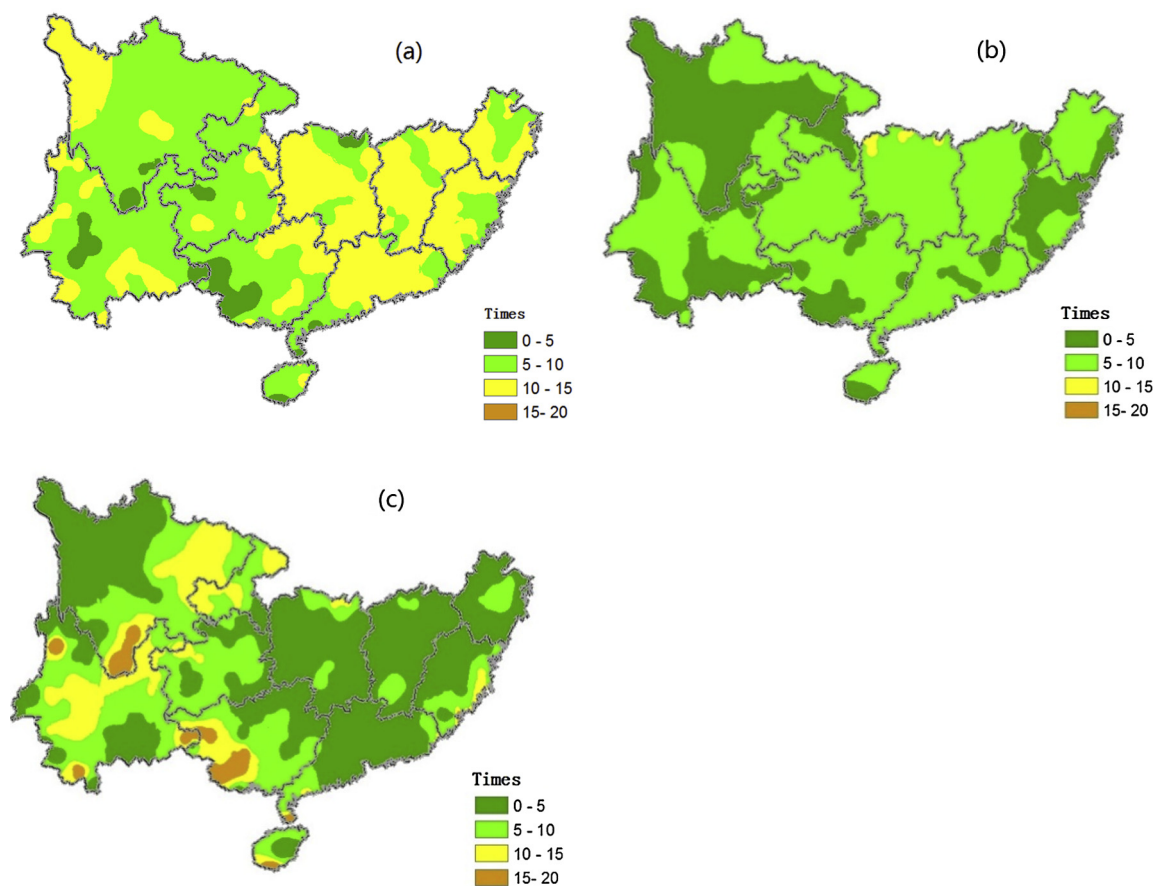


Fig. 8. Spatial distribution of droughts from 1961 to 2010 in the study area: (a) mild drought, (b) moderate drought and (c) severe drought.

Table 1

Water resource carrying capacity for major crops in three regions.

Region	Crop	Growth season	Precipitation (mm)	Crop water productivity (kg/m ³)	Water carrying capacity for crop (kg/m ²)
SWC	Winter wheat	Nov. to Apr.	214	1.32	0.26
	Middle rice	May to Sept.	832	0.71	0.55
	Maize	May to Sept.	832	1.70	1.38
	Region	Year	1136		0.73
SYR	Early rice	May to July	592	0.72	0.36
	Middle rice	June to Sept.	624	0.71	0.46
	Late rice	July to Oct.	468	0.63	0.26
	Region	Year	1489		0.33
SC	Early rice	Apr. to July	893	0.72	0.57
	Late rice	Aug. to Nov.	517	0.63	0.28
	Region	Year	1650		0.42

3.2.3. Agricultural water resource carrying capacity

Table 1 shows the regional averages of WRCCR for major crop growth seasons in the three regions. The water capacity in SWC region was 0.26, 0.55 and 1.38 kg/m² for winter wheat, middle rice and maize, respectively. Winter precipitation in SWC region was small, so the water resource carrying capacity was much lower for winter wheat than that for middle rice and maize. Although middle rice and maize grew during the same season, the water productivities between the two crops were quite different. The water productivity for rice was 0.71 kg/m³ and that for maize was 1.70 kg/m³ because maize is a C4 crop with high water use efficiency. The water capacity in SYR region was 0.46 kg/m² for middle rice, which was higher than that for early rice (0.36 kg/m²) and late rice (0.26 kg/m²). The water carrying capacity of early rice (0.57 kg/

m²) in the SC region was two times that of late rice (0.28 kg/m²). Thus, the water resource carrying capacity was different among crops in a region or for the same crops among the three regions.

The regional agricultural water resource carrying capacity was affected by the crop types and planting proportions of each crop and by the regional climate. On average, WRCCR in SWC region (0.73 kg/m²) was far higher than that in SYR (0.33 kg/m²) and SC regions (0.42 kg/m²) (Fig. 9). WRCCR exhibited a slight upward trend in all three sub-regions because of the development of agricultural technology (Fig. 9). The WRCCR in SWC (Fig. 9a) had low values from 1961 to 1964, from 1975 to 1981, and from 1987 to 1994, which was inconsistent with the annual precipitation trend (Fig. 5) and might be related to lower winter wheat planting proportions (Fig. 10a). The WRCCR in SYR showed a phase change

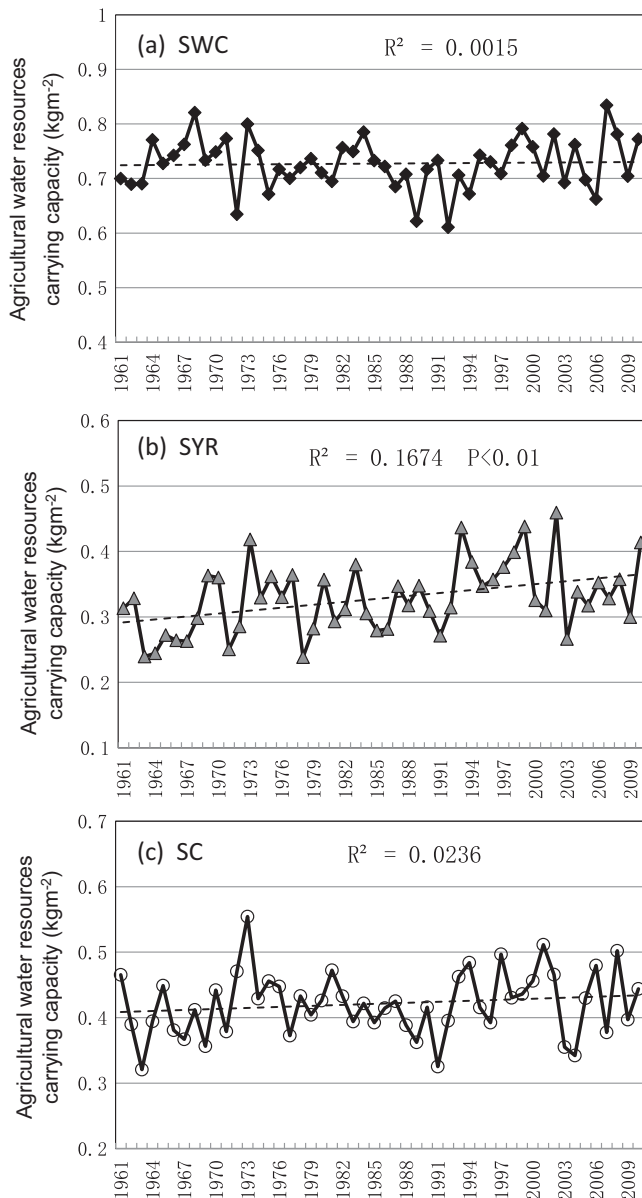


Fig. 9. Time variations of agricultural water resource carrying capacity from 1961 to 2010 in the three regions.

(Fig. 9b). Low values appeared during the 1960s and 1980s, which was roughly consistent with the annual precipitation trend and the greater middle rice planting area (Fig. 10b). In SC (Fig. 9c), an obvious declining trend was found during the late 1980s, which was contrary to the changes in the degree of agricultural droughts. In SC, the peak of WRCCR appeared during the 1970s, and low values mainly appeared in 1963, 1992, 2003 and 2004, which coincided very well with the variations in precipitation. The crop planting proportions varied slightly since the 1980s (Fig. 10c).

3.3. Effects of meteorological droughts on the agricultural water resource carrying capacity

The correlations between ADI and WRCCR in the three regions were significant ($P < 0.1\%$) (Fig. 11). In SWC region, WRCCR dropped to less than 0.7 kg/m^2 when moderate droughts occurred (Fig. 11a). In SYR region, WRCCR dropped to less than 0.3 kg/m^2 when moderate agricultural droughts occurred (Fig. 11b). In SC region

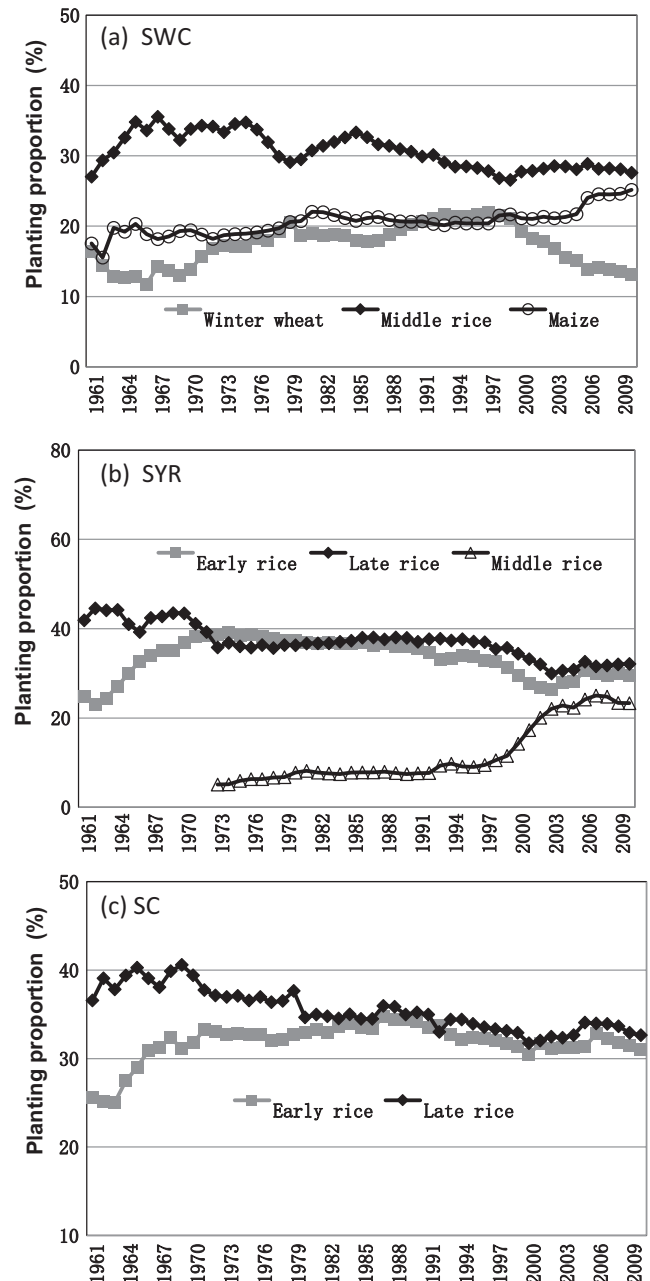


Fig. 10. Planting proportions of major crops from 1961 to 2010 in the three regions.

(Fig. 11c), WRCCR dropped to less than 0.4 kg/m^2 when meteorological droughts occurred. WRCCR in SC region dropped substantially in response to droughts and exhibited the most rapid decline among the three regions. This result indicates that WRCCR was more sensitive to droughts in SC and SYR regions than in SWC region during the past 50 years, where the rice planting areas were much greater than that in SWC region. On the other hand, the different levels of drought in SWC region had a minimal effect on WRCCR.

WRCCR and its sensitivity to the drought intensity were different for different crops in the same region or for the same crop in different regions because of differences in precipitation and crop water use efficiency (Fig. 12). Among all the crops, the largest difference in WRCCR was found between the two upland crops. The WRCCR for maize was much higher than that for winter wheat and also dropped more quickly than that for winter wheat as the

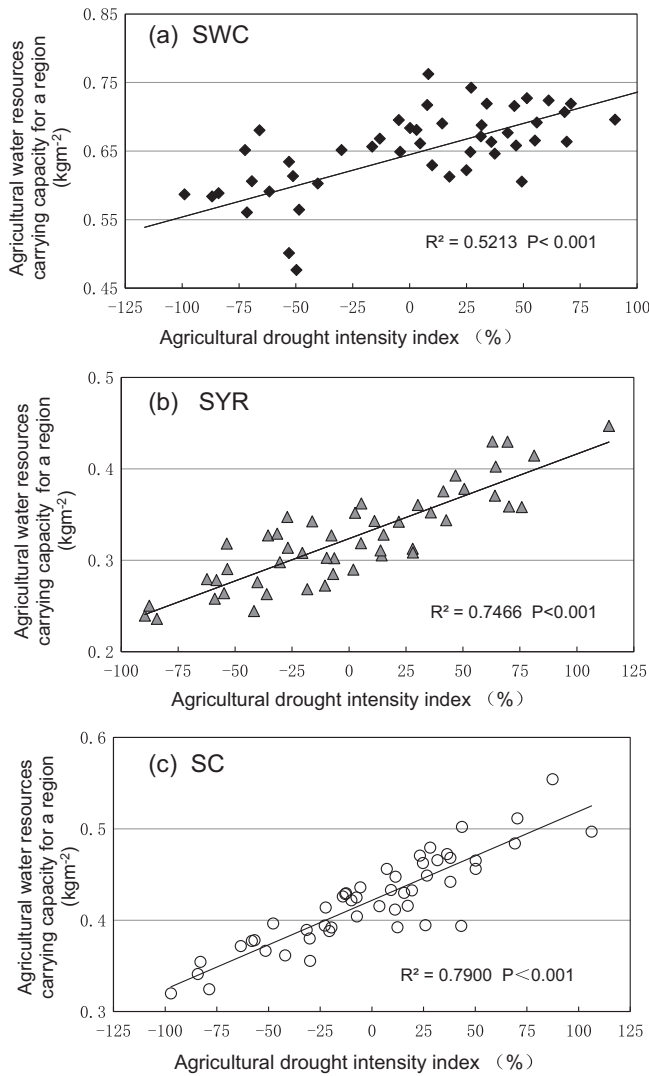


Fig. 11. Relationships between agricultural drought intensity index and agricultural water resource carrying capacity in SWC (a), SYR (b) and SC (c).

drought intensity increased. When moderate droughts occurred, the WRCCC for maize dropped to less than 1.0 kg/m², and the WRCCC for winter wheat decreased to around 0.2 g/m² (Fig. 12a, b). Regional differences in the WRCCC were significant for paddy crops. The WRCCC for middle rice in SWC dropped more slowly than that in SYR as the drought intensity increased. When moderate droughts occurred, the WRCCC for middle rice in SYR dropped to 0.4 g/m² or less, and the WRCCC for middle rice in SWC was reduced to around 0.55 g/m² (Fig. 12c, d). The WRCCC for early rice dropped more slowly than in SYR as the drought intensity increased. When droughts occurred, the WRCCC for early rice dropped below 0.4 g/m² in SC and below 0.35 g/m² in SYR (Fig. 12e, f). The WRCCC for late rice in SC and SYR regions was almost identical. When severe droughts occurred, the WRCCC values for late rice in both regions fell to below 0.26 g/m² (Fig. 12g, h). Among all the crops, the ARCCC values for maize in SWC and middle rice in SYR were more sensitive than those for the other crops.

3.4. Effects of meteorological droughts on agriculture production

The effects of meteorological droughts on agriculture in southern China were discussed in this section by analyzing drought

events in each region from 1961 to 2010. The ADI, AWRC, DEI, DHR and MY for total food crops were computed for each drought year and region. The AWRC and MY for single crops were also computed for each drought year and region. Negative AWRCs indicate that WRCCC or WRCCR was reduced by droughts during the crop growth season. Negative or low values of MY indicate that the regional agriculture or crops were affected by droughts. Meanwhile, high DEI and DHR values indicate that droughts were widespread and caused serious crop losses.

Seventeen drought years occurred in SWC (Table 2). Among all the typical drought years, the moderate drought years comprised the largest proportion, specifically, 8 years, or 47% of the total number. There were seven severe drought years which comprised 41% of the total number of drought years. In contrast, mild droughts occurred in only 2 years, or 12% of the total number. During most of the drought years, the AWRC for the region was negative and the MY was less than 2.0, which indicates that WRCCR and crop yield were obviously affected by droughts in this region. During the two mild drought years, drought effects on agricultural water resource carrying capacity and crop yield were also significant because droughts occurred during the main crop growth season, as indicated by the large DEI and DHR values. During the moderate drought and severe drought years, droughts clearly reduced the agricultural water resource carrying capacity and crop yield, especially in 1972 and 2006 (Table 2). Unlike middle rice and maize which are grown during the rainy season, the winter is grown in the dry season and is often affected by droughts in SWC. The AWRC for winter wheat was negative for 14 years, which comprised 82% of the total number of drought years. When adequate water storage was present during the rainy season from the previous year, such as in 1978 and 1987, droughts had little effect on winter wheat yield.

Eighteen drought years occurred in SYR (Table 3). Mild droughts were dominant (9 years). The number of severe drought and moderate drought years was 6 and 3, respectively, which were obviously lower than those in SWC. During most of the drought years, the AWRCs had negative values and the MYs were negative or less than 2.0, except in 1979. The agricultural practices in 1979 were affected by policy factors: agricultural investment increased significantly and the drought resistant capacity increased, so the yield of food crops obviously increased. The AWRCs matched the ADI well during most of the drought years, and both indices were negative during moderate and severe drought years. Reductions in crop yield for the region and in late rice were recorded during the three severe drought years, which suggested that the WRCCR was reduced to a point lower than normal under severe drought conditions, and caused a decrease the crop yield. Among the three types of rice, late rice was the most vulnerable to droughts. Reductions in the crop yield during some drought years were caused by both droughts and heat injury, such as the yield reduction of middle season rice in 1988. Table 3 shows that more frequent consecutive drought years occurred in SYR region; for instance, three consecutive drought years occurred from 1966 to 1968 and from 2007 to 2009, and two consecutive drought years occurred from 1963 to 1964 and from 1978 to 1979. Crop yield reductions during these consecutive drought years were not obvious during the second year, in which the time trend yields of the crops were also affected.

Sixteen drought years occurred from 1961 to 2010 in SC, which was the fewest among the three regions. These drought years were classified into seven mild, five moderate and four severe drought years based on their drought intensity. The AWRCs for the region during all these drought years were negative, which indicates the best correlation with the ADI among the three regions. The MYs during the mild and moderate drought years were below those during normal years. The DEIs and DHRs during the severe drought years were over 22.9 and 46.0, respectively. Decreases in food crop

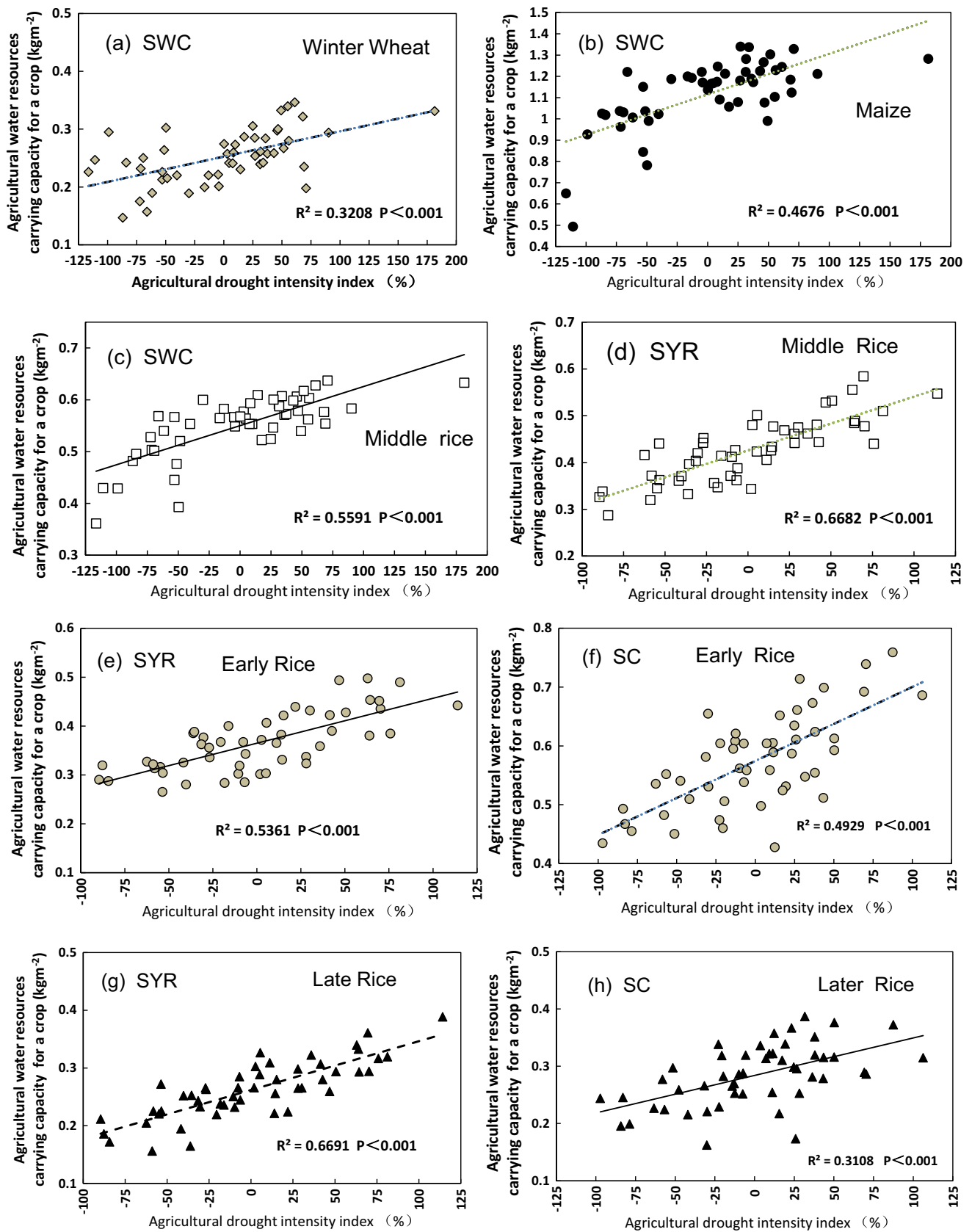


Fig. 12. Relationships between the agricultural water resource carrying capacity for major crops and the drought intensity index.

Table 2

Drought indices, AWRCs and meteorological crop yields at each drought year from 1960 to 2010 in SWC region.

Drought intensity	Year	ADI	DEI	DHR	AWRC for region	MY for food crops	AWRC and MY for single crops					
							Winter wheat		Middle rice		Maize	
							AWRC	MY	AWRC	MY	AWRC	MY
Mild	1979	−29.9	26.0	49.1	1.0	−1.2	−25.2	−2.0	9.0	−0.7	6.4	−6.2
	1988	−40.4	20.3	40.0	−6.5	−3.3	−12.8	−5.0	0.6	−2.1	−8.4	−2.9
Moderate	1969	−66.0	–	–	5.5	−2.2	−37.8	−12.0	3.3	−2.4	9.5	0.8
	1978	−53.0	27.3	29.7	−1.6	0.7	−15.8	3.2	3.0	1.8	3.1	3.6
	1987	−61.6	24.8	40.3	−8.3	1.9	−24.8	6.1	−1.9	1.5	−9.8	−3.4
	1989	−53.1	15.5	31.1	−22.3	0.9	−10.6	−2.5	−19.1	−0.4	−24.3	2.6
	1992	−49.8	26.8	58.9	−26.1	−0.5	19.7	0.3	−28.6	0.0	−29.9	−5.6
	1994	−48.6	21.7	39.9	−12.5	−2.1	−14.8	−3.4	−5.4	−1.5	−11.2	−1.8
	2003	−69.4	17.4	52.6	−6.3	0.7	−0.9	−1.3	−8.8	2.2	−7.6	−1.9
	2005	−51.3	18.1	52.2	−4.9	2.5	4.6	−2.3	−13.5	4.0	−7.2	2.6
Severe	1963	−86.9	–	–	−9.5	1.8	−41.9	−1.6	−12.4	0.5	−8.1	1.5
	1972	−110.8	–	–	−37.7	−6.7	−2.3	0.9	−21.9	−8.0	−55.7	−7.6
	1975	−71.5	–	–	−13.1	2.0	−8.2	−7.7	−8.5	3.8	−13.7	2.5
	1981	−84.0	9.0	59.0	−8.7	−2.8	−4.1	−7.4	−10.0	−2.8	−8.7	−4.8
	2006	−116.5	35.5	62.1	−32.2	−5.1	−10.4	1.9	−34.4	−7.4	−41.8	−4.1
	2009	−99.0	15.1	42.7	−9.0	0.7	16.8	3.8	−22.1	−0.1	−16.9	−1.0
	2010	−72.3	31.5	69.6	1.0	0.0	−30.6	−8.2	−4.1	1.4	−7.1	3.8

Note: “–” indicates that no data are available.

Table 3

Drought indices, AWRCs and meteorological crop yields during each drought year from 1960 to 2010 in the SYR region.

Drought intensity	Year	ADI	DEI	DHR	AWRC for region	MY for food crops	AWRC and MY for single crops					
							Early rice		Middle rice		Late rice	
							AWRC	MY	AWRC	MY	AWRC	MY
Mild	1964	−41.8	–	–	−24.6	0.0	−11.0	−5.3	−15.4	–	−25.8	4.5
	1967	−36.2	–	–	−18.9	−1.0	5.5	−2.9	−22.1	–	−37.3	−1.3
	1968	−30.4	–	–	−8.1	2.0	3.2	−1.7	−1.6	–	−11.3	4.3
	1974	−35.5	–	–	0.9	0.3	6.3	4.7	−7.1	–	−3.8	−8.5
	1985	−40.2	21.8	58.0	−14.8	−0.7	−23.3	−2.9	−13.1	−4.5	−3.9	2.2
	1988	−26.9	26.3	44.6	−3.2	−0.9	−8.1	0.4	6.0	−9.3	0.2	−1.0
	2004	−31.5	10.1	60.4	1.5	1.2	−0.7	1.8	−5.4	−0.7	−7.3	1.4
	2005	−20.6	10.4	61.4	−5.0	−2.1	0.6	−0.4	−16.5	−1.9	−16.4	−2.1
	2008	−27.1	6.7	33.8	7.1	0.7	−2.6	0.9	3.6	1.2	1.2	0.1
Moderate	1966	−54.8	–	–	−18.5	−0.6	−13.5	4.3	−19.1	–	−15.9	0.4
	1979	−62.4	–	–	−13.8	7.4	−10.5	4.2	−2.5	–	−22.0	6.8
	1986	−58.1	27.2	54.6	−14.1	0.3	−14.2	3.8	−12.9	−0.8	−14.2	−3.5
	2003	−59.0	36.4	68.3	−20.4	−1.4	−11.9	−0.9	−25.0	0.5	−40.5	−2.4
	2007	−53.7	25.4	61.4	−1.8	−0.5	−27.4	−0.2	3.2	−1.5	3.7	−0.5
	2009	−53.4	14.4	40.9	−10.4	0.9	−16.8	2.8	−15.0	0.3	−14.2	0.3
Severe	1963	−89.6	–	–	−26.2	−0.5	−20.6	4.0	−23.6	–	−19.5	−1.1
	1971	−87.7	–	–	−22.8	−0.9	−12.6	−0.8	−12.6	–	−29.2	−6.9
	1978	−84.3	28.9	60.2	−27.2	−4.5	−22.0	2.1	−32.7	–	−34.5	−0.5

Note: “–” indicates that no data are available.

yields were observed when the AWRCs for each region dropped below −19%. Table 4 shows that the decreases in the crop yield during the drought years were less than those in SWC and SYR. This result indicates high drought resistance capability in SC.

3.5. Relationship between the WRCCR and planting structure under meteorological drought conditions

To investigate the inter-annual variations of natural drought, actual agriculture drought and the relationship with planting structure alteration, we took WRCCR scaled by the ratio of the average planting proportions of major crops over the total planting area of food crops in the three regions as the reference WRCCR for each year. Comparing the WRCCRs that were based on the average planting scale of major crops and the WRCCRs that were based on the actual planting scale of major crops showed that the different

planting scales of the major crops resulted in different WRCCRs during drought years (Fig. 13). In order to investigate the effects of different planting structure on drought relief, we analyzed the relationship between planting proportion for each crop and WRCCR in typical drought years (Fig. 14).

The differences between the actual WRCCR and the reference WRCCR in SWC region were positive in the 1960s and the 2000s, but negative in the other years. The difference between the actual WRCCR and the reference WRCCR was significantly related to the local crop planting structure (Figs. 13a and 10a). When the planting proportion of winter wheat was reduced, WRCCRs increased obviously compared to the reference WRCCR. Although drought intensity in the 2000s was over that in the late of 1980s and the early of the 1990s, only in two years actual drought (shown by EDI) exceeded that in the 1980s and in the 1990s due to the increase in WRCCR (Fig. 13a). During drought years, the difference

Table 4

Drought indices, AWRCs and meteorological crop yields during each drought year from 1960 to 2010 in the SC region.

Drought intensity	Year	ADI	DEI	DHR	AWRC for region	MY for food crops	AWRC and MY for single crop			
							Early rice		Late rice	
							AWRC	MY	AWRC	MY
Mild	1962	−31.5	–	–	−7.6	1.3	1.2	0.2	−6.2	−1.2
	1964	−22.8	–	–	−6.5	−2.1	−17.5	0.4	19.3	−1.2
	1966	−30.1	–	–	−9.9	−0.2	14.0	−4.3	−42.7	3.2
	1969	−29.9	–	–	−15.7	1.0	−7.5	−1.2	−22.1	0.2
	1986	−22.4	22.9	39.1	−1.8	−3.9	5.2	−2.7	−19.2	−4.3
	1988	−20.6	21.1	45.5	−7.9	−5.1	−19.8	−1.1	12.4	−9.2
	1989	−42.0	17.4	51.5	−14.2	2.0	−11.2	1.0	−24.0	3.2
Moderate	1967	−51.4	–	–	−13.0	0.6	−21.5	6.2	4.9	−1.9
	1971	−56.7	–	–	−10.3	1.0	−3.8	−1.1	−20.9	0.4
	1977	−63.4	–	–	−11.8	1.6	−6.7	−4.7	−20.0	8.2
	2007	−58.1	18.9	47.0	−10.5	1.3	−16.0	2.0	−2.3	0.6
	2009	−47.7	15.8	41.0	−5.8	1.3	−5.9	2.4	−8.8	0.1
Severe	1963	−97.2	–	–	−24.1	−1.2	−24.3	−4.0	−14.0	3.8
	1991	−78.7	32.1	46.0	−23.0	−0.8	−20.7	−0.7	−29.8	−0.8
	2003	−82.9	22.9	50.1	−15.9	1.2	−18.7	0.4	−13.5	3.8
	2004	−84.2	27.8	49.4	−19.1	−1.6	−14.1	1.9	−31.0	−5.5

Note: “–” indicates that no data are available.

between the actual WRCCR and the reference WRCCR in SWC region obviously decreased with the increasing of the planting proportions of winter wheat, which is a dry season crop (Fig. 14a). WRCCR significantly increased when the anomaly of the planting proportion of middle rice decreased by 5% to 10% (Fig. 14b). WRCCR increased as the maize planting area increased (Fig. 14c). Therefore, the wheat and rice planting areas in SWC region should be reduced and maize planting area should be expanded to improve the agricultural water resource carrying capacity and mitigate the effects of droughts on agriculture.

In SYR region, the differences between actual WRCCR and reference WRCCR were positive in the 2000s, but negative in the 1960s. The variation of the differences during the 1970s and the 1990s was very small. This result was in consistent with the change of the planting structure in this region. Large adjustments to the crop planting structure in SYR region occurred around the year 2000, when a sudden change was observed (Fig. 13b and Fig. 10b). When the planting proportion of middle rice was increased, WRCCRs increased obviously. In the 2000s, the drought intensity (shown by ADI) was severer than that in the 1980s, but the actual drought was not severer than that in the 1980s. The early rice growth season is the rainy season, so the water resource carrying capacity would increase to a certain extent by planting more, and AWCCR could be increased by 5% to 10% when the planting proportion is substantially reduced by approximately 30% (Fig. 14d). Rainfall during the main growth season of late rice was not as abundant as that for early rice, so the reduction of planting area should be reduced to increase the water resource carrying capacity (Fig. 14e). In this region, expanding the middle season rice planting scale could increase the water resource carrying capacity (Fig. 14f). For a water-consumption cropping system, the water resource carrying capacity would increase when the double-season rice planting area is sufficiently reduced. Drought events in SYR region have increased since the year 2000 drought events, so the planting scale of single rice should be expanded to reduce the risk of droughts.

In SC region, the differences between actual WRCCR and reference WRCCR were positive after the 1980s. These were lower than in the other regions due to small variations of crop planting proportions in this period (Figs. 13c and 10c). There is plenty of rainfall during the early rice growth season in SC region, so no clear relationships were found between the planting proportion and water carrying capacity (Fig. 14g). In contrast, rainfall during the late rice

growth season is much less. Thus, the water carrying capacity could be increased by reducing the planting proportion (Fig. 14h), which would decrease drought effects on agriculture in SC region. This study shows that we can enhance the agricultural water resource carrying capacity in humid southern China by adjusting the planting structure to mitigate the effects of droughts on agriculture.

4. Discussion

In this study, we found that the agricultural drought intensity index ADI had a good relationship with the DEI, AWRC and MY. Analyses for each typical drought year showed that the AWRCs for the entire study area were negative for 88% of the drought years. In particular, the AWRC declined significantly during severe drought years (Fig. 15a). Meanwhile, the MYs of food crops were less than 2.0 during almost all the drought years and negative during 50% of the drought years (Fig. 15b). These results strongly suggest that the ADI can sufficiently indicate the occurrence and effects of droughts during most drought years and that the ADI is suitable for drought monitoring in rice planting areas, such as southern China.

The AWRC was significantly correlated with the yield of food crops and the actual area covered by droughts. The anomalies of WRCCRs during all the drought years were less than 10% and dropped below −20% during severe drought years (Fig. 15a). Meanwhile, AWRC had a good relationship with MY ($P < 0.001$). When AWRCs were below −20%, MYs were negative (Fig. 15c). These results showed that AWRC could describe drought effects on agriculture. This index was related to the planting structure and the crop growth season. Thus, this index is also adaptable to the study area.

Some uncertainties existed in the correlations among the ADI, AWRC, and MY. The agricultural water resource carrying capacity during some severe drought years was not less than normal, which might be related to low proportions of water consumption crops and dry spells not occurring during the major crops' growth seasons, such as in 1963 in SWC and in 2003 in SC. On the other hand, some mild droughts occurred during the main crop season or at a critical stage of growth, and AWRC was low, such as in 1988 in SWC and in 1985 in SYR. Food production was affected more

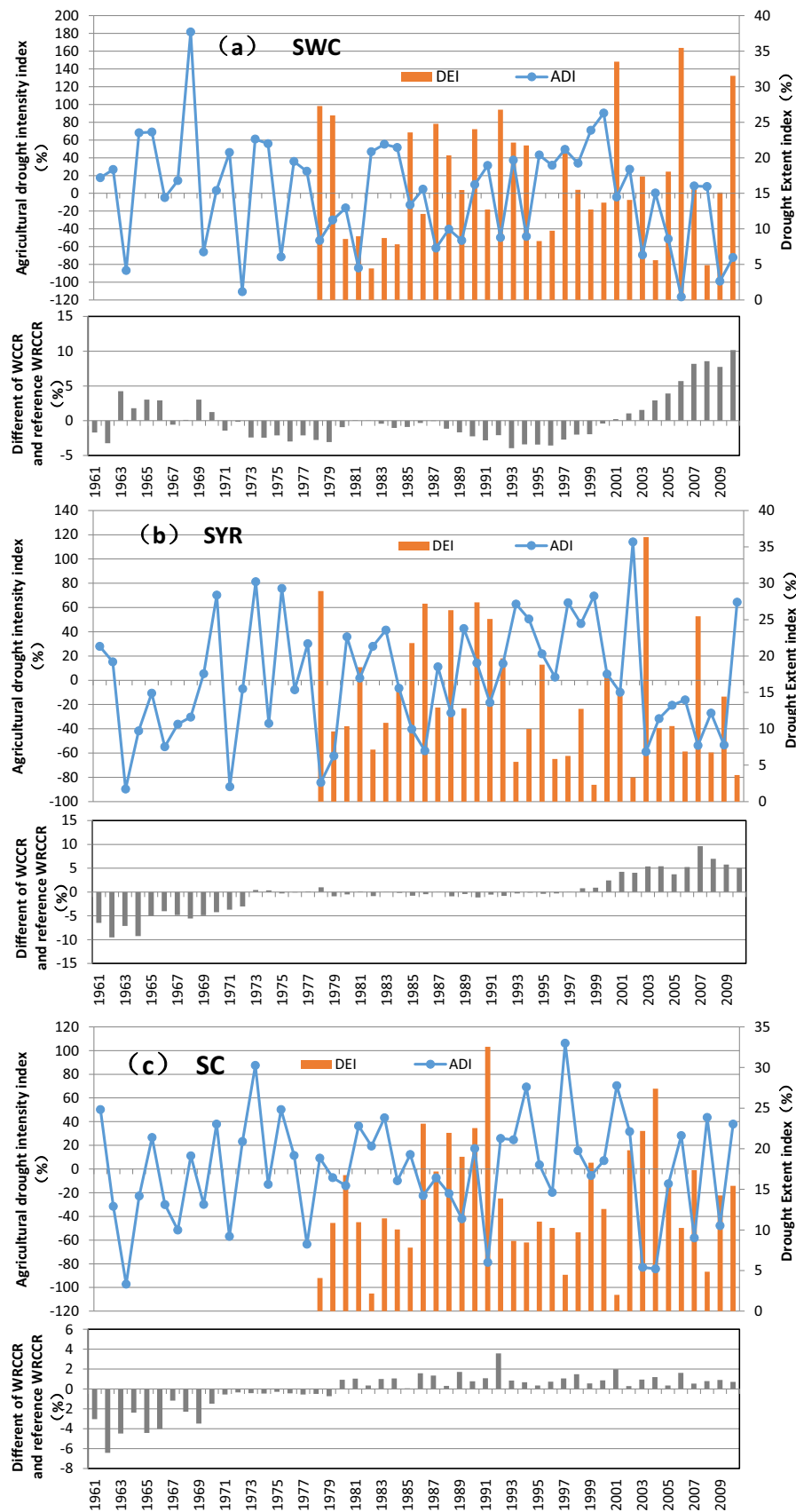


Fig. 13. The variations of drought intensity (shown by ADI), actual drought (shown by DEI) and the difference between WRCCR based on actual crop planting proportion and reference WRCCR based on averaged crops planting proportion in three regions during 1961 and 2010.

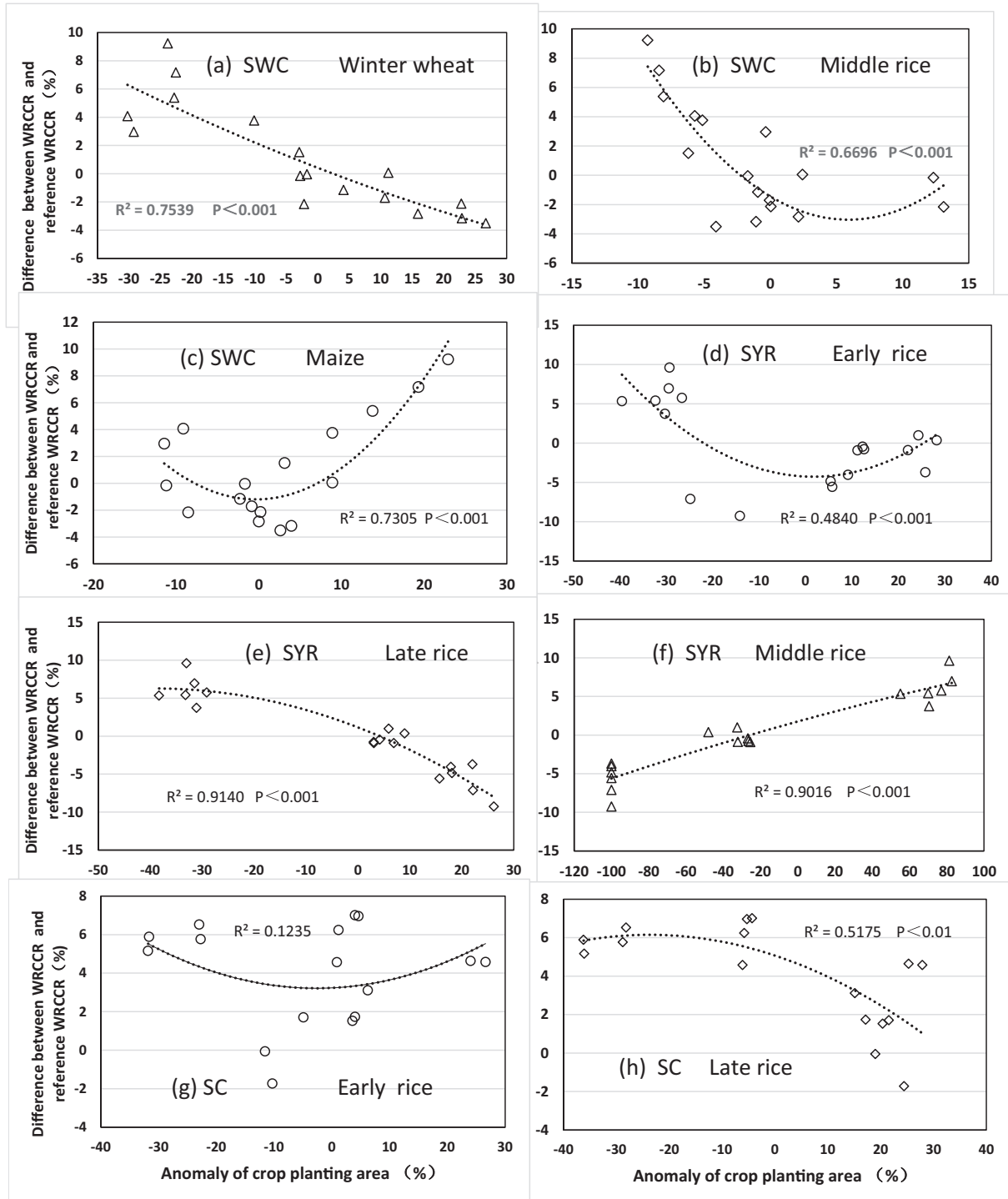


Fig. 14. Relationship between the difference of WRCCR (same as Fig. 13) and the anomaly of the crop planting area during drought years in three regions.

severely by drought in these cases. Rice is the major crop in southern China. Around 50% to 70% of water consumption for rice production is from blue water (Wang et al., 2014). Meanwhile, southern China has good irrigation systems, and the effective irrigation area is approximately 30%–64% of the crop sown area (National Bureau of Statistics of China, 2010). The MYs were not always negative during every drought year because of irrigation.

Some uncertainties existed in the correlations among the ADI, AWRC, and MY. We did not find any significant relationships

among the DEI, HDR and effective irrigation area in the study region, which might be related to the uncertainty in the spatial and temporal distributions of the droughts. The ADI does not consider the effects of irrigation. We found ADI was sensitive to precipitation variations in the three regions, and is more sensitive in SYR and SC than in SWC which has complex terrain and wet and dry seasons.

Notwithstanding these limitations, these results offered comprehensive information regarding the effects of meteorological

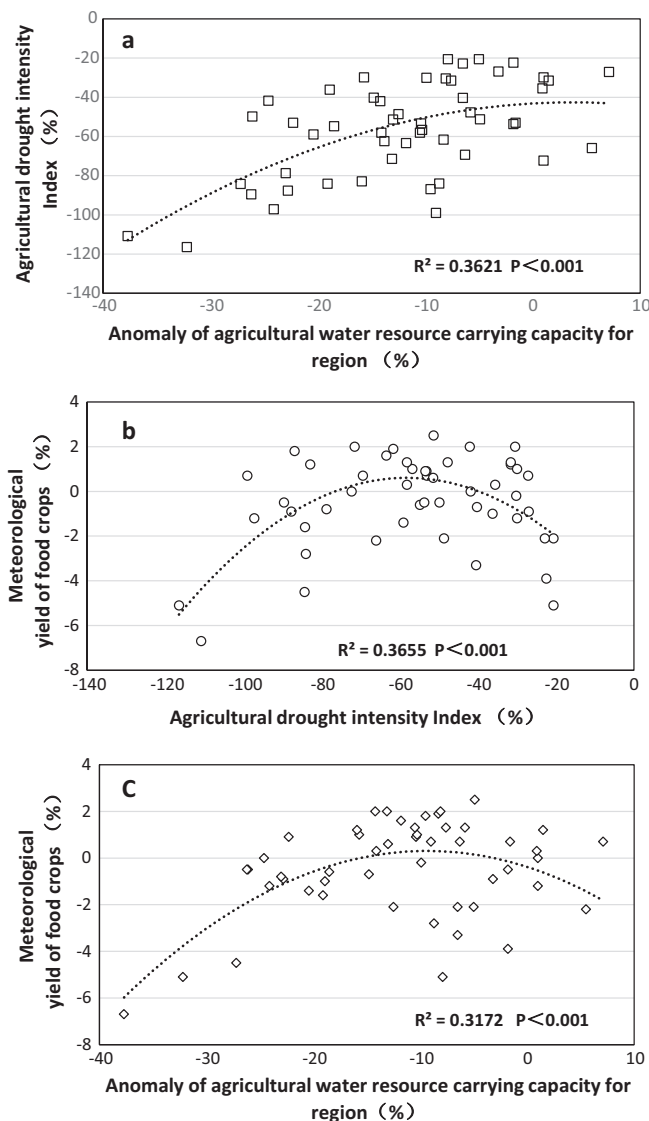


Fig. 15. Variations of the AWRC with ADI, the MY with ADI, and the MY with AWRC in drought years (not including 1979 in SYR).

droughts on the agricultural water resource in the humid regions of southern China at regional scales and over a large time scale (50 years). Important conclusions could be drawn to provide greater insight into crop–climate interactions and sustainable crop production in China.

5. Conclusions

This study investigated meteorological droughts and their effects on the agricultural water resource in the humid regions of southern China. The findings demonstrated that the agricultural drought intensity index (ADI) based on rainfall and water demand for crops was significantly correlated with the actual drought occurrence extension index ($p < 1\%$). ADI is suitable for drought assessment in rice planting areas in southern China. The agricultural water resource carrying capacity index (AWRCC) was constructed based on the concepts of carrying capacity and crop water productivity to estimate the upper of available water resource in crops growth season. The AWRCC was significantly correlated with regional average food crop yields and drought disaster areas ($P < 1\%$). This result confirmed that the index could reflect the

drought conditions and the upper limit for agricultural water resource productivity. Droughts occurred approximately one third of the years between 1961 and 2010. AWRCC was lower than normal in 88% of the total 51 drought events. This result indicated agricultural water resources were restricted under drought condition, and thus lead to crops yield reduction. Water resource carrying capacity is decided by planting structure in greatly degree. Regional planting structure adjustment countermeasures were proposed based on the relationship between the agricultural water resource carrying capacity and the planting structure to improve agricultural water resources for drought resistance. Reducing the planting area of dry season crops and rice could improve the AWRCC in drought years at the region with dry and wet season. Likewise, reducing the planting area of double-season rice could improve AWRCC in regions with double-season rice cropping systems.

In summary, these results can provide useful insights into developing effective and adaptive strategies of agricultural drought defense for policymakers at a regional scale. Water resource availability and adjustment of planting structure should be considered especially in drought resistant decision-making. In addition, other factors such as farm practices, the adopted crop varieties should be considered.

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References

- Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration guidelines for computing crop water requirements. In: FAO Irrigation and Drainage Paper 56 Rome, pp. 65–134.
- Bola, G., Mabiza, C., Goldin, J., Kujinga, K., Nhapi, I., Makurira, H., Mashauri, D., 2014. Coping with droughts and floods: a case study of Kanyemba, Mbire District, Zimbabwe.
- Burn, D.H., Hesch, N.M., 2007. Trends in evaporation for the Canadian prairies. *J. Hydrol.* 336 (1–2), 61–73.
- Chen, H.P., Sun, J.Q., Chen, X.L., 2013. Future changes of drought and flood events in China under a global warming scenario. *Atmos. Oceanic Sci. Lett.* 6 (1), 8–13.
- Falkenmark, M., 1995. Coping with Water Scarcity Under Rapid Population Growth. Conference of SADC Minister, Pretoria.
- Falkenmark, M., Rockström, J., 2006. The new blue and green water paradigm: breaking new ground for water resources planning and management. *J. Water Resour. Plann. Manage.* 132 (3), 129–132.
- Fang, S.N., Yang, J.J., Zhou, G.S., 2011. Change trend and distributive characteristics of agro-meteorological disasters in China in recent 30 years. *J. Natural Disasters* 20, 69–73.
- Gao, X., Shi, Y., Zhang, D., Giorgi, F., 2012. A high resolution climate change simulation of the 21st century over China by RegCM3. *Chin. Sci. Bull.* 57, 1188–1195.
- Gleick, P.H., 1987. Regional hydrologic consequences of increases in atmospheric CO_2 and other trace gases. *Clim. Change* 10, 137–161.
- Gong, D.Y., Ho, C.H., 2002. Shift in the summer rainfall over the Yangtze River valley in the late 1970s. *Geophys. Res. Lett.* 29, 71–78.
- Harris, J., Scott, K., 1999. Carrying capacity in agriculture: global and regional issues. *Ecol. Econ.* 29, 443–461.
- Hayes, M.J., Svoboda, M.D., Wilhite, D.A., et al., 1999. Monitoring the 1996 drought using the standardized precipitation index. *Bull. Am. Meteorol. Soc.* 80, 429–438.
- Hixon, M.A., 2008. Carrying Capacity. Reference Module in Earth Systems and Environmental Sciences, from Encyclopedia of Ecology, 528–530.
- Huang, F., Li, B., 2010a. Assessing grain crop water productivity of China using a hydro-model-coupled-statistics approach Part I: Method development and validation. *Agric. Water Manag.* 97 (7), 1077–1092.
- Huang, G., 2004. An index measuring the interannual variation of the East Asian Summer monsoon—the EAP index. *Adv. Atmos. Sci.* 21 (1), 41–52.
- Huang, H.P., 2011. Characteristics and causes of drought in China from 1949 to 2007. *J. Arid Land Resour. Environ.* 10 (24), 94–98.
- Huang, S., Chang, J., Leng, G., Huang, Q., 2015. Integrated index for drought assessment based on variable fuzzy set theory: a case study in the Yellow River basin, China. *J. Hydrol.* 527, 608–618.

- Huang, W., Yang, X., Li, M., 2010. Evolution characteristics of seasonal drought in the south of China during the past 58 years based on standardized precipitation index. *Trans. CSAE* 26 (7), 50–59 (in Chinese with English abstract).
- IPCC, 2013. *Climate change 2013: the physical science basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Summary for Policymakers*.
- Jensen, M.E., 1968. Water consumption by agricultural plants. In: Kozlowski, T.T. (Ed.), *Water Deficits and Plants Growth*, vol. II. Academic Press, New York, pp. 1–22.
- Karl, T.R., Riebsame, W.E., 1989. The impact of decadal fluctuations in mean precipitation and temperature on runoff a sensitivity study over the United States. *Clim. Change* 15, 423–447.
- Kotteck, M., Grieser, J., Beck, C., et al., 2006. World map of the Koppen-Geiger climate classification updated. *Meteorol. Zeitschr.* 15, 259–263.
- Larissa, G., Francisco, M.C.C., Susana, M.A.D., Bifulco, Carlo, Stagge, J.H., Marta, S.R., Van Lanen, Henny A.J., 2015. Links between meteorological drought indices and yields (1979–2009) of the main European crops, drought R&SPI technical report No. 36. Wageningen University, the Netherlands Instituto Superior de Agronomia, Portugal University of Oslo, Norway.
- Leng, G., Tang, Q., Rayburg, S., 2015a. Climate change impacts on meteorological, agricultural and hydrological droughts in China. *Global Planet. Change* 126, 23–34.
- Leng, G., Huang, M., Tang, Q., Leung, L.R., 2015b. A modeling study of irrigation effects on global surface water and groundwater resources under a changing climate. *J. Adv. Model. Earth Syst.* 7 (3), 1285–1304.
- Lettenmaier, D.P., Gan, T.Y., 1990. Hydrologic sensitivities of the Sacramento-San Joaquin river basin, California, to global warming. *Water Resour. Res.* 26, 69–86.
- Liu, J., Savenije, H.H.G., 2008. Food consumption patterns and their effect on water requirement in China. *Hydrol. Earth Syst. Sci.* 12 (3), 887.
- Meadows, D.H., Meadows, D.L., Randers, J., Behrens, W.W., 1972. *The Limits to Growth. A report for the Club of Rome's Project on the Predicament of Mankind*. Universe Books, New York, 88–128.
- Mishra, A.K., Singh, V.P., Desai, V.R., 2009. Drought characterization: a probabilistic approach. *Stoch. Environ. Res. Risk A.* 23 (1), 41–55.
- National Bureau of Statistics of China, 2010. *Compilation of Agricultural Statistical Data for 30 Years Since Reforming and Opening*. China Statistics Press, Beijing, China.
- Palmer, W., 1965. *Meteorological Drought*. Research paper no.45. U.S. Department of Commerce Weather Bureau.
- Panagoulia, D., 1992. Impact of GISS-modeled climate changes on catchment hydrology. *Hydrol. Sci. J.* 37, 141–163.
- Park, R.E., Ernest, W.B., 1921. *Introduction to the Science of Sociology*. [Third edition, 1969]. The University of Chicago Press, Chicago.
- Peel, M.C., Finlayson, B.L., McMahon, T.A., 2007. Updated world map of the Koppen-Geiger climate classification. *Hydrol. Earth Syst. Sci.* 11, 1633–1644.
- Quiring, S., 2015. Hydrology, floods and droughts|drought. In: *Encyclopedia of Atmospheric Sciences*. 2nd ed., pp. 193–200.
- Savenije, H.H.G., 2000. Water scarcity indicators; the deception of the numbers. *Phys. Chem. Earth* 25 (3), 199–204.
- Seidl Tisdell, C.A., 1999. Carrying Capacity reconsidered: from Malthus population theory to cultural carrying capacity. *Ecol. Econ.* 31 (3), 395–408.
- Sui, Y., Huang, W., Yang, X., Li, M., 2012a. Characteristics and adaption of seasonal drought in southern China under the background of global climate change. I. Change characteristics of precipitation resource. *Chin. J. Appl. Ecol.* 23 (7), 1875–1882.
- Sui, Y., Huang, W., Yang, X., Li, M., 2012b. Characteristics and adaption of seasonal drought in southern China under the background of global climate change. II. Spatiotemporal characteristics of drought for wintering grain and oil crops based on crop water deficit index. *Chin. J. Appl. Ecol.* 23 (9), 2467–2476.
- Tao, C.S., 1998. A sensitive coefficient of rice under insufficient irrigation. *J. Jiangsu Agric. Coll.* 19 (2), 59–61.
- United Nations Convention to Combat Desertification (UNCCD), 2003. *Drought, Living With Risk: An Integrated Approach to Reducing Societal Vulnerability to Drought*. http://www.unccd.int/Lists/SiteDocumentLibrary/Regions/Asia/meetings/regional/TPN5_7_2003/annex3.pdf.
- Vimal, M., Keith, A., Cherkauer, 2010. Retrospective droughts in the crop growing season: Implications to corn and soybean yield in the Midwestern United States. *Agric. For. Meteorol.* 150, 1030–1045.
- Wang, T., Wang, H.J., Wang, O.H., Otter, Y.Q., Gao, L.L., Suo, T., Furevik, L., Yu, 2013. Anthropogenic forcing of shift in precipitation in Eastern China in late 1970s. *Atmos. Chem. Phys. Discuss* 13, 11997–12032.
- Wang, H.J., 2001. The weakening of the Asian monsoon circulation after the end of 1970s. *Adv. Atmos. Sci.* 18, 376–386.
- Wang, Y., Wu, P., Engel, B., Sun, S., 2014. Application of water footprint combined with a unified virtual crop pattern to evaluate crop water productivity in grain production in China. *Sci. Total Environ.* 497–498, 1–9.
- Wilhite, D.A., 2000. Drought as a natural hazard: concepts and definitions. In: Wilhite, D.A. (Ed.), *Drought: A Global Assessment, Natural Hazards and Disasters Series*. Routledge Publishers, UK, pp. 3–18. Chapter 1.
- World Meteorological Organization, 2010. *Guide to Agricultural Meteorological Practices*, WMO-No. 134. World Meteorological Organization, Switzerland.
- Xiao, J.F., Liu, Z.D., Duan, A.W., Liu, Z.G., 2008. Study on Jensen model at each growing stage for main crops in China. *Water saving irrigation*, 1–8.
- Xu, L., Li, M.Y., Liu, A.J., 2012. The evolution of drought and its impact on agriculture in recent years. *J. Arid Land Resour. Environ.* 26, 53–56.
- Yan, Z.Z., Gao, Y.C., Yuan, Y., Ma, Y.L., 2009. National standards of People's Republic of China (GB/T 24438.1-2009): *Natural disaster information statistics-Part 1: Basic indicators*. China Standard Press, Beijing, China.
- Zhao, J.F., Xu, J.W., Xie, X.M., Lu, H.Q., 2016. Drought monitoring based on TIGGE and distributed hydrological model in Huaihe River Basin, China. *Sci. Total Environ.* 553, 358–365.