

A comprehensively quantitative method of evaluating the impact of drought on crop yield using daily multi-scale SPEI and crop growth process model

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Abstract The quantitative evaluation of the impact of drought on crop yield is one of the most important aspects in agricultural water resource management. To assess the impact of drought on wheat yield, the Environmental Policy Integrated Climate (EPIC) crop growth model and daily Standardized Precipitation Evapotranspiration Index (SPEI), which is based on daily meteorological data, are adopted in the Huang Huai Hai Plain. The winter wheat crop yields are estimated at 28 stations, after calibrating the cultivar coefficients based on the experimental site data, and SPEI data was taken 11 times across the growth season from 1981 to 2010. The relationship between estimated yield and multi-scale SPEI were analyzed. The optimum time scale SPEI to monitor drought during the crop growth period was determined. The reference yield was determined by averaging the yields from numerous non-drought years. From this data, we propose a comprehensive quantitative method which can be used to predict the impact of drought on wheat yields by combining the daily multi-scale SPEI and crop growth process model. This method was tested in the Huang Huai Hai Plain. The results suggested that estimation of calibrated EPIC was a good predictor of crop yield in the Huang

Huai Hai Plain, with lower RMSE (15.4 %) between estimated yield and observed yield at six agrometeorological stations. The soil moisture at planting time was affected by the precipitation and evapotranspiration during the previous 90 days (about 3 months) in the Huang Huai Hai Plain. SPEI_{G90} was adopted as the optimum time scale SPEI to identify the drought and non-drought years, and identified a drought year in 2000. The water deficit in the year 2000 was significant, and the rate of crop yield reduction did not completely correspond with the volume of water deficit. Our proposed comprehensive method which quantitatively evaluates the impact of drought on crop yield is reliable. The results of this study further our understanding why the adoption of counter measures against drought is important and direct farmers to choose drought-resistant crops.

Keywords Evaluating · Crop growth process model · EPIC · Drought · SPEI · Huang Huai Hai Plain

Introduction

Drought is a recurring and complex natural hazard (Wilhite and Buchanan-Smith, 2005), which can be an abstract natural disaster (Hagman et al., 1984; Wilhite, 1996). The world area which will experience extreme drought conditions will increase by 29 % during this century (Burke et al., 2006), with drought frequency and duration for a serious drought event also likely to rise (Blunden et al., 2011). Drought may lead to unfavorable natural and social phenomena (Shen et al., 2007), such as exacerbated desertification of land, significant crop yield losses, increased social violence, and fire disaster in the natural ecosystem (Bruins and Berliner, 1998; MacDonald, 2007; Pausas, 2004; Quiring and Papakryiakou, 2003). Drought can also influence regional or global food

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production and food security (Dilley, 2005; Helmer and Hilhorst, 2006; Narasimhan and Srinivasan, 2005).

The Huang Huai Hai Plain is one of the largest grain production zones in China (Shi et al., 2014). Planting areas for wheat occupy 45 % of the whole nation, and maize occupies 33 % (Guo et al., 2010). However, the Huang Huai Hai Plain is prone to drought (Chen et al., 2011). The increased occurrence and severity of drought may be caused by higher evapotranspiration as a result of increasing temperature (Sheffield and Wood, 2008). Climate change has influenced the hydrological ecology and agricultural environment in many regions of the world, including the Huang Huai Hai Plain (Gao et al., 2006; Huntington, 2006; Sheffield and Wood, 2008). A quantitative evaluation of the impact of frequent droughts on crop yield in the Huang Huai Hai Plain is urgently needed to improve agriculture water resource management.

It is a key for quantitative evaluation of the impact of drought on crop yield to choose a suitable drought monitoring index. There are three common drought indices used to monitor agricultural drought and soil water balance, the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010; Wang et al., 2014), Standardized Precipitation Index (SPI) (McKee et al., 1993), and Palmer Drought Severity Index (PDSI) (Palmer, 1965). The use of SPI with multi-scale characteristics can monitor different kinds of drought, including meteorological drought, agricultural drought, hydrological drought, and socio-economic drought (Guttman, 1998; Hayes et al., 1999). However, SPI only considers precipitation as a factor of drought, and cannot monitor drought caused by higher temperature. The influence of temperature on drought can be characterized using PDSI (Dubrovsky et al., 2009). Although PDSI lacks the ability of multi-scale, it can assess different types of drought. Overall, a drought index which includes a multi-time scale and temperature factor is required. It is appropriate for SPEI to be used to study agricultural droughts influenced by global warming. However, the monthly SPEI used commonly has a lower time resolution of 1 month and cannot identify drought in the day or crop growth period. Therefore, a more refined or higher time resolution SPEI needs to be developed to assess drought in the crop growth period.

In previous studies, the detrend method which uses statistical yield data for evaluating the impact of drought on crop yield is used. This method has the limitation that it cannot exclude other unfavorable factors (floods, diseases, and pests) influencing crop yield. Other crop growth models can remove the unfavorable factors and estimate impact of drought influencing crop yield. The crop growth model can be used to improve the management of agricultural water resources and consider the effects of extreme climate change. Most crop growth models can project or estimate crop yield by looking at

the physiological process during crop growth. These models include DSSAT (Decision Support System for Agrotechnology Transfer) (Jones et al., 2003; Wu et al., 2014), EPIC (Environmental Policy Integrated Climate) (Williams, 1989), WFOST (WORLD FOOD STUDIES) (Eitzinger et al., 2004), and AquaCrop (Raes et al., 2009). The crop growth model can be a good tool to analyze the variation of water deficit and the impact of the water deficit on crop yield (Wu et al., 2014). They have also been used to analyze the impact of climate variability on crop production (Alexandrov and Hoogenboom, 2000; Chavas et al., 2009; Thomson et al., 2006; Xiong et al., 2010). Crop models have been demonstrated to have a good ability to estimate or predict the crop growth and yield, taking into account different stress factors including precipitation, temperature, etc. (Liu et al., 2011). Therefore, well-calibrated and tested crop models are useful in this study to estimate crop yield in drought or non-drought (not wet and not dry) years. Although a method based on the crop growth model estimation has been conducted in previous studies (Jia et al., 2012; Wu et al., 2014), the yield used as a reference could be the potential yield of the crop with sufficient water and fertilizer (Jia et al., 2012). However, it is nearly impossible to meet all the conditions without stresses impacting the crop growth process. Thus, it is necessary to determine a more reasonable reference yield as there is a lack of studies on quantitative evaluation of the impact of drought on crop yield.

The goal of this study was to propose a new comprehensive quantitative method that assesses the impact of drought on crop yield by combining SPEI and the crop growth process model. Our study was conducted at 28 meteorological stations. The winter wheat yield was estimated at each station using calibrated cultivar coefficients, and the relationship between estimated yield and multi-scale SPEI were analyzed. We found the optimum time scale SPEI to monitor drought in the crop growth period based on the development of a more refined SPEI. Drought and non-drought years were identified by using SPEI. A reference yield was determined by combining the simulated yields with multiple non-drought years; the reference yield was used to determine the impact of drought quantitatively. This study may provide some reference understanding in the measurement of the impact of drought and guide farmers to actively respond to extreme weather events to ensure food security.

Study area and data sources

The Huang Huai Hai Plain is in northern China, between 31° E and 42° E, and 114° N and 121° N. It belongs to part of the Huaihe River basin, the Yellow River basin, and the Haihe River basin. According to the principle of comprehensive agricultural regionalization, the Huang Huai Hai Plain was

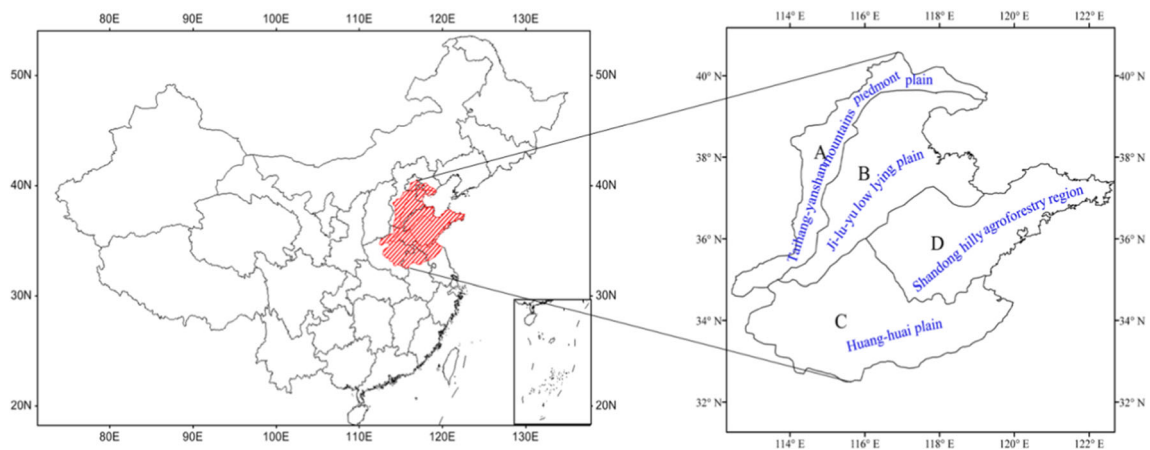


Fig. 1 The study area (A Taihang-yanshan mountains piedmont plain, B Ji-lu-yu low lying plain, C Huang Huai plain, D Shandong hilly agroforestry region)

divided into four sub-regions and shown in Fig. 1; the Huang Huai Hai Plain is the main region of arable land in China (Fig. 2). The meteorological stations are shown

in Table 1. The 28 stations were evenly distributed across the study area, thus representing the spatial pattern of water conditions in the area.

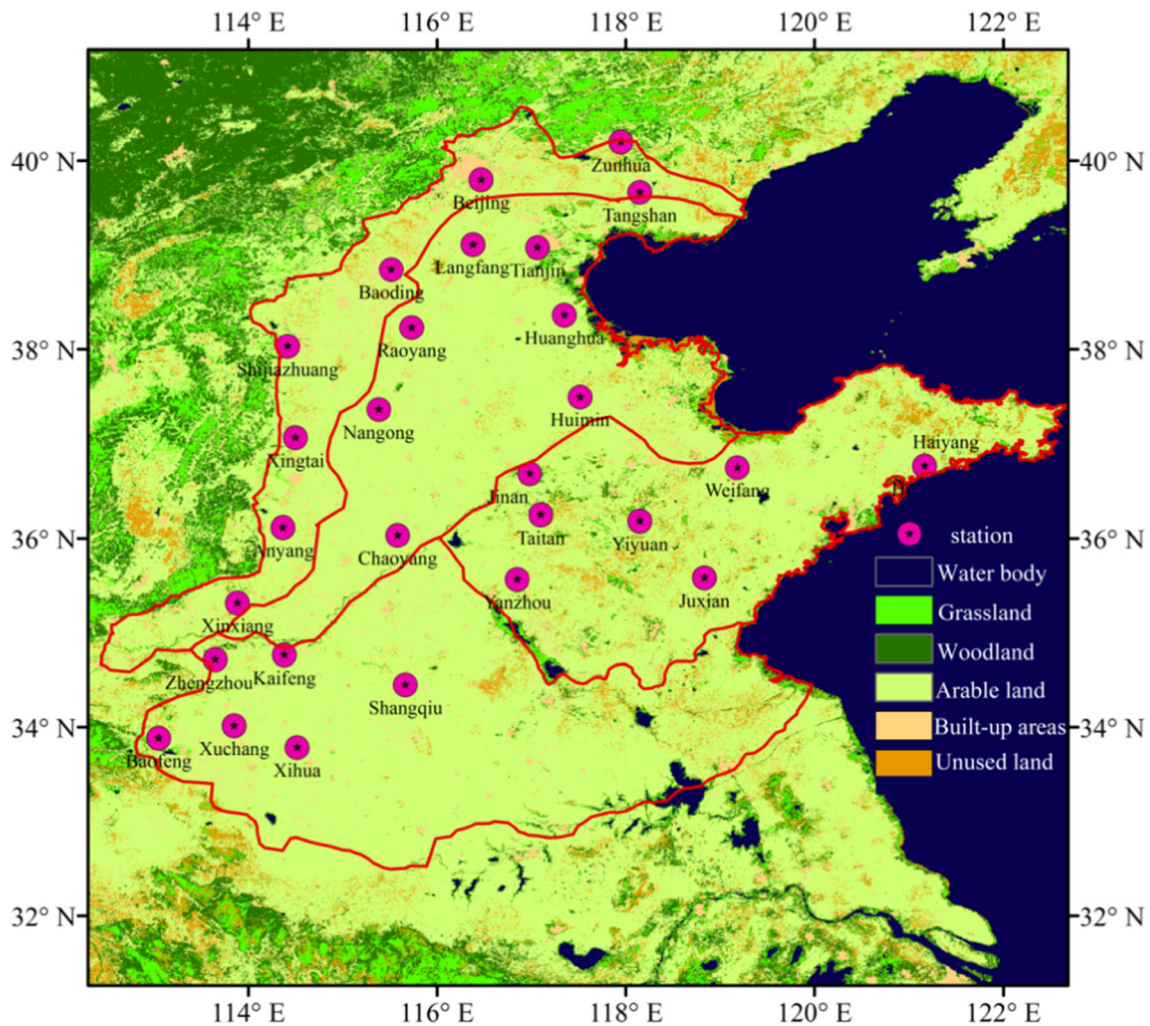


Fig. 2 Spatial distribution of land use and the meteorological stations in the Huang Huai Hai Plain (the red circles denote the spatial distribution of the 28 meteorological stations; the rectangles in the legend identify the different land use types)

Table 1 Basic information table of 28 meteorological stations

Station name	Longitude (°E)	Latitude (°N)	Elevation (m)	Station name	Longitude (°E)	Latitude (°N)	Elevation (m)
Zunhua (ZH)	117.95	40.20	55	Jinan (JN)	116.98	36.68	52
Beijing (BJ)	116.47	39.80	31	Taishan (TSH)	117.10	36.25	1534
Tangshan (TS)	118.15	39.67	28	Yiyuan (YY)	118.15	36.18	303
Langfang (LF)	116.38	39.12	9	Anyang (AY)	114.37	36.12	76
Tianjin (TJ)	117.07	39.08	3	Chaoyang (CY)	115.58	36.03	43
Baoding (BD)	115.52	38.85	17	Juxian (JX)	118.83	35.58	107
Huanghua (HH)	117.35	38.37	7	Yanzhou (YZ)	116.85	35.57	52
Raoyang (RY)	115.73	38.23	19	Xinxiang (XX)	113.88	35.32	73
Shijiazhuang (SJZ)	114.42	38.03	81	Kaifeng (KF)	114.38	34.77	73
Huimin (HM)	117.52	37.50	12	Zhengkou (ZZ)	113.65	34.72	110
Nangong (NG)	115.38	37.37	27	Shangqiu (SQ)	115.67	34.45	50
Xingtai (XT)	114.50	37.07	77	Xuchang (XC)	113.85	34.02	67
Haiyang (HY)	121.17	36.77	65	Baofeng (BF)	113.05	33.88	136
Weifang (WF)	119.18	36.75	22	Xihua (XH)	114.52	33.78	53

From 1980 to 2010, at the stations, daily meteorological data were obtained from the China Meteorological Administration, which included the maximum air temperature (°C), minimum temperature (°C), the relative humidity (%), the sunshine duration (h), the daily average wind speed (m/s), and precipitation (mm). The solar radiation was calculated using sunshine duration, using the Ångström function (Wang et al., 2015). To obtain continuous meteorological data for each station, 28 meteorological stations in the Huang Huai Hai Plain were selected, with stations missing any data being removed from the study. Land cover data (MCD12Q1) in 2010 were obtained from the United States Geological Survey (USGS). The type of land use included water body, grassland, woodland, arable land, built-up land, and unused land (Liu et al., 2003). Using observations of crop growth of winter wheat which are grown under five irrigation regimes at Gucheng in the Huang Huai Hai Plain during 2007–2008, six Agro-meteorological stations (Tangshan, Baoding, Huanghua, Huimin, Weifang, and Juxian) are selected to validate the calibration of the crop growth model. Observational data was taken between 2005 and 2010 at 36 wheat experimental sites. Over the Huang Huai Hai Plain, the observational data were used to determine the planting and harvest dates at the 28 stations (Lu and Fan, 2013), and the planting dates were shown in Table 2.

Table 2 Sowing dates of winter wheat at the 28 selected stations

Sowing date	Station name
October 5	Zunhua, Beijing, Tangshan, Langfang, Tianjin, Baoding
October 8	Huanghua, Raoyang, Shijiazhuang, Huaimin, Nangong, Xingtai, Haiyang, Weifang, Jinan, Taishan
October 10	Yiyuan, Anyang, Chaoyang, Juxian, Yanzhou, Xinxiang, Kaifeng, Zhengzhou
October 15	Shangqiu, Xuchang, Baofeng, Xihua

Methodology

In order to choose the optimal drought indicator and identify the drought and normal years, multi-scale SPEI were used in our study; crop growth model was employed to simulate the yield in each year from 1981 to 2010. A method in evaluating the impact of drought on crop yield was proposed and validated; the flow chart for evaluating the method was shown in Fig. 3.

Multi-scale SPEI

The SPEI index requires precipitation and evapotranspiration factors. The Hargreaves method was used to obtain the estimated evapotranspiration factor (Stagge et al., 2015; Hargreaves and Samani, 1982). Previous, a daily SPEI calculation method has been developed which was used to assess drought in the Huang Huai Hai Plain with good results (Wang et al., 2015). The detail of the calculations used to determine daily SPEI have been reported previously (Wang et al., 2015). Daily SPEI data were obtained at each station. In this study, the Grow Season Length (GSL) scale SPEI was used to monitor water conditions across the whole growing season (from sowing to harvest). Using this scale daily, SPEI on the day before winter wheat harvest can identify whether water will be in surplus or deficit during the

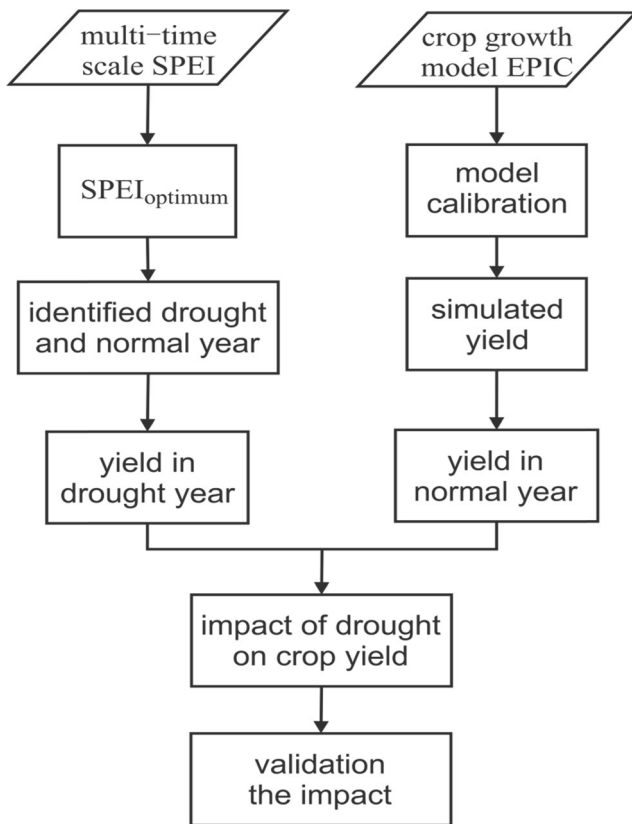


Fig. 3 The flow chart for the proposed evaluating method in impact of drought in crop yield

whole growing season (SPEI_G). To determine whether precipitation and temperature impact crop yield before sowing, 10 time scales were used, GSL plus 10 days before sowing SPEI_{G10}, SPEI_{G20}, SPEI_{GSL30}, SPEI_{G40}, SPEI_{G50}, SPEI_{G60}, SPEI_{G70}, SPEI_{G80}, SPEI_{G90}, and SPEI_{G100}. The daily SPEI on the days before winter wheat harvest are calculated. The drought classifications of SPEI are shown in Table 3.

Crop growth model description

EPIC is organized into the modules climate data, soil data, the atmosphere-plant-soil interface, and agricultural management

Table 3 Classification used for the SPEI (McKee et al., 1993; Paulo et al., 2012)

Drought class	SPEI values
Extreme wet	SPEI ≥ 2.0
Severe wet	1.5 < SPEI < 2.0
Moderate wet	1 < SPEI ≤ 1.5
Mild wet	0.5 < SPEI ≤ 1.0
normal	-0.5 ≤ SPEI ≤ 0.5
Mild dry	-1 < SPEI < -0.5
Moderate dry	-1.5 < SPEI ≤ -1.0
Severe dry	-2 < SPEI ≤ -1.5
Extreme dry	SPEI ≤ -2.0

measurements (Williams, 1989). EPIC was used to estimate the crop growth process, soil water balance, and crop yield (Williams and Singh, 1995). The EPIC model has been recognized as an important tool for assessing the impact of climate variability on crop growth and development (Chavas et al., 2009). The simulated principle and process of the crop growth model is shown in Fig. 4.

EPIC model uses the harvest index estimating crop yield and determining the proportion of the above-ground biomass conversion for production.

$$YLD_j = (HI_j)(B_{AG}) \tag{1}$$

where YLD_j is the yield of crop *j* (t/ha), HI_j is the harvest index of crop *j*, and B_{AG} is the above-ground biomass of crop *j*. Under the condition without environmental stresses, the harvest index shown a trend of nonlinear increasing from 0 to 1; its computation formula is as follows:

$$HIA_i = HI_j \left(\sum_{K=1}^i (\Delta HUFH_K) \right) \tag{2}$$

where HIA_i is the harvest index in the day *i* and HUFH is the heat unit (accumulated temperature) factors affecting the harvest index; its computation formula is as follows:

$$HUFH_i = \frac{HUI_i}{HUI_i + \exp(6.50 - 10.0HUI_i)} \tag{3}$$

HUI_i is the heat unit index. Set this constant is to ensure HUFH increases from 0.1 (HUI_i = 0.5) to 0.9 (HUI_i = 0.9), because crop scan produce the most crop yields in the bottom half of the growth period; its computation formula is as follows:

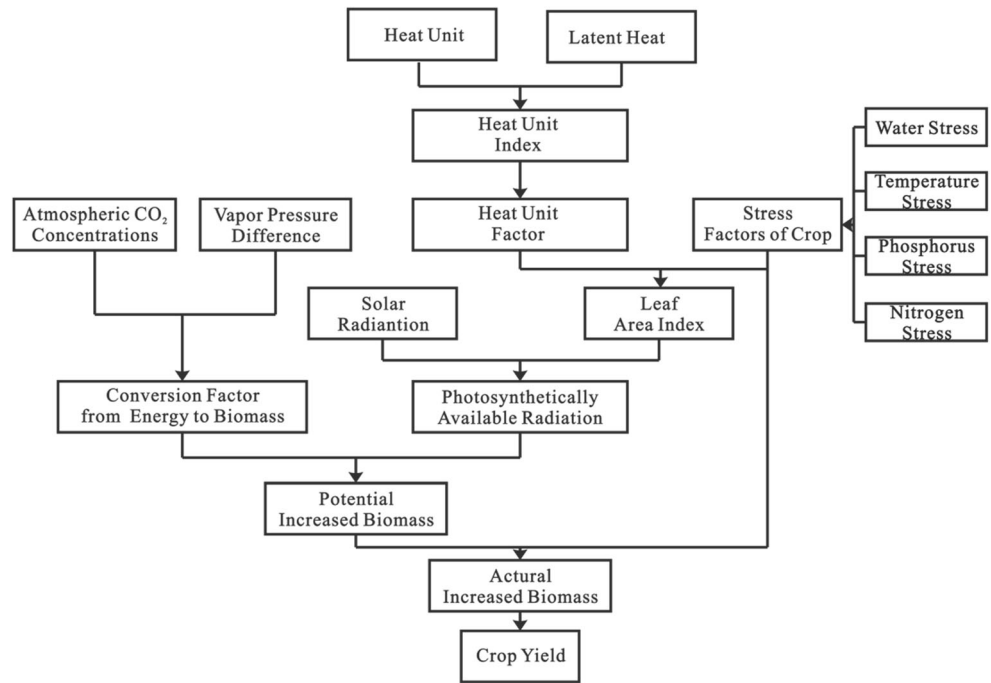
$$HUI_i = \frac{\left(\sum_{K=1}^i \right) HU_K}{PHU_j} \tag{4}$$

HUI_i is the heat unit index. HU_K is the heat unit in the day *k*, and PHU_j is the amount of latent heat crop *j* needed to mature. HU_K can be calculated by the following formula:

$$HU_K = \left(\frac{T_{mx,K} + T_{mn,K}}{2} \right) - T_{b,j} \quad HU_K > 0 \tag{5}$$

HU_K is the heat unit in the day *k*, T_{mx, K} is the highest temperature (°C) in the day *k*, T_{mn, K} is the lowest temperature (°C) in the day *k*. T_{b, j} is the base temperature (°C) crop *j* needed for growth; the crops will stop growing when it is lower than the temperature.

Fig. 4 The simulated principle and process of crop growth model



Another key variable calculating crop yield is the above-ground biomass; its computation formula is as follows:

$$B_{AG} = \sum_{k=1}^n (\Delta B_k) \tag{6}$$

ΔB_k is the increment of above-ground biomass in the day k , n is the number of days for crop growth, and its computation formula is as follows:

$$\Delta B_i = (\Delta B_{p,i})(REG) \tag{7}$$

ΔB_i is the increment of the above-ground biomass in the day i ; $\Delta B_{p,i}$ is the potential increment of the above-ground biomass in the day i . REG is the minimum stress factor for crop (including water stress factor, nutrient stress factor, temperature stress factor, radiation stress factor, and air stress factor). If without any stress, its value is 1. $\Delta B_{p,i}$ can be calculated by the following formula:

$$\Delta B_{p,i} = 0.001 (BE_j)(PAR_i)(1 + \Delta HRLT_i)^3 \tag{8}$$

BE_j is the crop parameter for energy converted to biomass (kg ha MJ⁻¹ m²). PAR_i is the photosynthetic effective radiation in the day i (MJ m⁻²), $\Delta HRLT_i$ is the variation between actual sunshine time and theoretical sunshine time (h); it can be calculate by latitude and sequence (January 1 as 1, May 31 as 365 or 366). PAR_i can be calculated by the following formula:

$$PAR_i = 0.5(RA_i)[1 - \exp(-0.165LAI_i)] \tag{9}$$

RA_i is the solar radiation in the day i (MJ m⁻²); LAI_i is the crop leaf area index in the day i .

The leaf area index can be expressed through heat unit, crop stresses, and crop growth stages. From the emergence to the crop leaf area began to decline, the leaf area index can be calculated by the following formula:

$$LAI_i = LAI_{i-1} + \Delta LAI \tag{10}$$

$$\Delta LAI = (\Delta HUF)(LAI_{mx})(1 - \exp(5.0(LAI_{i-1} - LAI_{mx})))\sqrt{REG_i} \tag{11}$$

LAI is the leaf area index, HUF is the heat unit factor, and Δ is the change of every day. Sub mx is the possible maximum value,

$$HUF_i = \frac{HUI_i}{HUI_i + \exp(ah_{j,1} - (ah_{j,2})(HUI_i))} \tag{12}$$

$ah_{j,1}$ and $ah_{j,2}$ are two crop parameters.

From the leaf area began to decline to the end of the growing season, LAI is calculated in accordance with the following formula:

$$LAI = LAI_{mx} \left(\frac{1 - HUI_i}{1 - HUI_o} \right)^{adj} \tag{13}$$

ad is a crop parameter that controls the decreasing rate of the crop leaf area for crop j .

HUI_o is the corresponded heat unit index value when the leaf area began to decline.

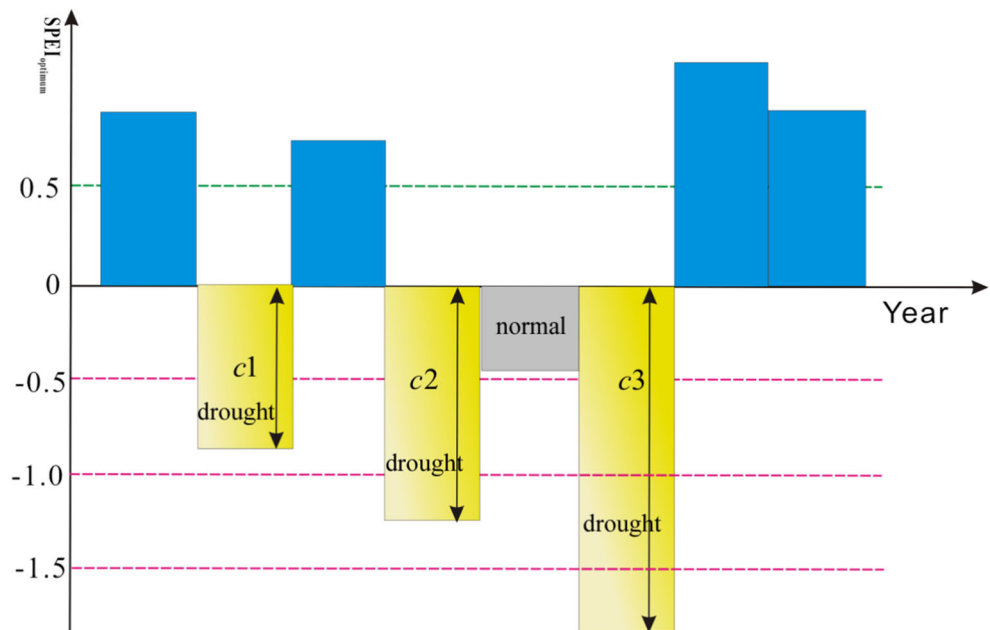
We calibrated the cultivar coefficients of the EPIC observation at Gucheng station. The relative root mean square error (RMSE) for the observed and estimated crop yield was 0.19 t/ha. The correlation between the observed and estimated yields was 0.98. At the six selected stations (Tangshan, Baoding, Huanghua, Huimin, Weifang, and Juxian), the correlation between the observation and estimated crop yields was also calculated for the period 2003–2010. The normalized RMSE was 15.4 %, which indicated the EPIC was a good predictor for regional estimations (Tojo et al., 2007).

In this study, the crop growth process of winter wheat were estimated at the 28 selected stations over the past 30 years. Rainfed treatment was used to exclude the effect of irrigation which may alleviate drought. Fertilization data was collected before sowing and after wheat germination, with 80, 100, and 100 kg/ha of N, P, and K fertilizer applied, respectively (Zhang et al., 2013).

Evaluating the impact of drought on crop yield

This study investigated the relationship between the abovementioned 11 time scales SPEI and crop yield, based on crop growth model estimation. The relationship was expressed by Pearson’s correlation coefficient, and the optimum time scale SPEI (SPEI_{optimum}) was chosen to monitor drought during the crop growth period for winter wheat in the Huang Huai Hai Plain. The classification of SPEI specifies that an absolute value of less than or equal to 0.5 is considered non-drought conditions, and less than -0.5 is considered drought conditions; the threshold can exclude the wet and dry weather condition. SPEI_{optimum} can be used to determine the drought and non-drought (not dry and not wet) years (Fig. 5).

Fig. 5 Schematic diagram of SPEI_{optimum} in every year at a station (the yellow color is SPEI_{optimum} in drought year; the gray color is SPEI_{optimum} in non-drought year)



In this study, a reference yield was calculated based on identified non-drought years (Fig. 6). The reference yield was calculated at each station by averaging the estimated yield in non-drought years. The reference yield was calculated using the following Equation (1):

$$Yield_{i,normal_value} = \frac{Yield_{i,k1} + Yield_{i,k2} + \dots + Yield_{i,kn}}{n} \quad (14)$$

where $Yield_{i,normal_value}$ is the calculated reference yield, n is the number of the years experiencing non-drought conditions, and $Yield_{i, kn}$ is the estimated yield in the kn th non-drought year at i station based on crop growth model simulation.

In order to quantitatively evaluate the impact of drought on crop yield, the yield reduction rate was defined by combining the calculated reference yield and the estimated yield in a drought year at each station. The yield reduction rate is expressed as:

$$Yield_reduction_rate_{i,m} = \frac{Yield_{i,normal_value} - Yield_{i,m}}{Yield_{i,normal_value}} \times 100\% \quad (15)$$

where $Yield_reduction_rate_{i,m}$ is the percentage of crop yield reduction in m year with drought conditions at i station, $Yield_reduction_rate_{i,m} > 0$ results in a reduction in yield, and $Yield_reduction_rate_{i,m} < 0$ is increase in yield. $Yield_{i,m}$ is estimated yield in m year at station.

To test the above method in determining the impact of drought on crop yield, continuous crop yield data are required. There was no continuous observational crop yield data spanning from 1981 to 2010 at the 28 stations, and wheat yield data in statistical year books on a county scale do not distinguish the yield between

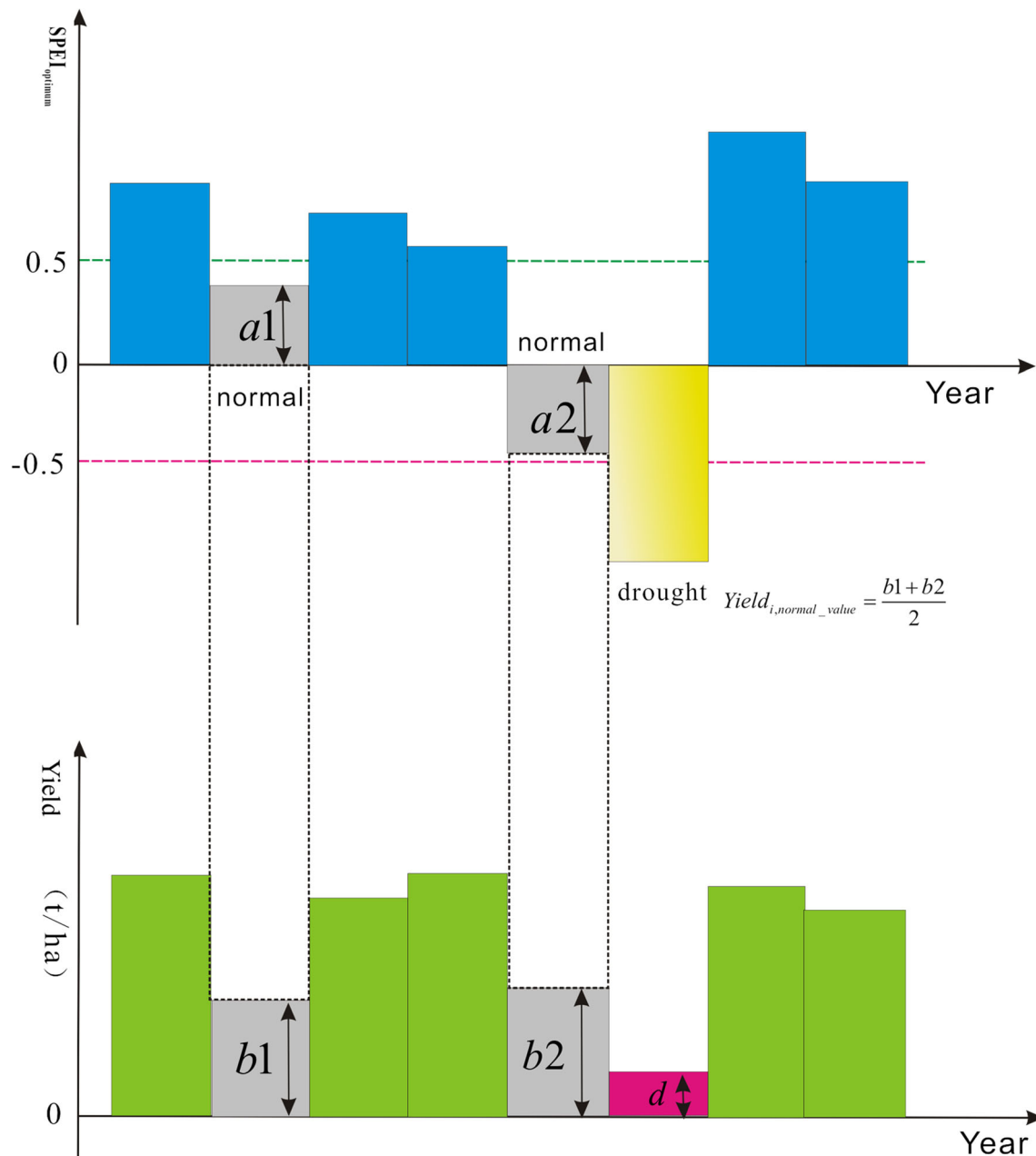


Fig. 6 Schematic diagram of the determined referential yield at a station (the red color is estimated yield in drought year at the bottom, the gray color is simulated yield in non-drought year at the bottom)

winter wheat yield and spring wheat yield. The winter wheat yields can be obtained at the provincial (or municipal) level, so the method described above was tested at the provincial (or municipal) level. The statistics on yield at a provincial (or municipal) scale shows there is a mixed effect yield from various social and natural environmental factors. When the statistical yield are influenced by drought, they may also be adversely affected by other natural factors (pest, frost, floods, and other natural disasters) or positively affected by the implementation of irrigation. When the drought occurred in the larger extent of the region and crop yield reduced for that year, it was assumed that the drought

conditions led to crop yield reducing as a result of the difficulty to meet all irrigation requirement to cope with the widespread drought (Wang et al., 2014). Therefore, $SPEI_{optimum}$ was used to determine the drought year at the provincial (or municipal) scale, with yield reduction in that year partly a result of the drought conditions. Therefore, yield reduction in the drought year can be used as a criterion to test the method described.

It is difficult to calculate the magnitude of the reduction in yield caused by drought only through statistical yield data. The Moving Average Evaluating Method (MAEM) which calculated the impact of drought based on statistical yield data

Table 4 Classification used for the Cronbach’s alpha

Reliability class	C_α
Very reliable	Value ≥ 0.9
More reliable	$0.8 \leq \text{value} < 0.9$
Acceptable	$0.7 \leq \text{value} < 0.8$
Suspicious	$0.6 \leq \text{value} < 0.7$
Poor reliable	$0.5 \leq \text{value} < 0.6$
Acceptable	Value < 0.5

that can be used as a reference (Zhang, 2004); MAEM can reduce the influence of technological progress on crop yield to an extent. In this study, a 5-year collection of the annual yield was used to calculate a reference yield and used as the normal yield to calculate the statistical yield (Zhang, 2004). We also calculated the change in yield based on the comprehensive

evaluating method (CEM) by combining the SPEI and crop growth process model simulation at provincial (or municipal) levels and the yield and $\text{SPEI}_{\text{optimum}}$ at the stations across the five provincial (or municipal) regions.

The result of MAEM being used as a reference increases the accuracy of CEM. When $\text{SPEI}_{\text{optimum}}$ is less than -0.5 , it predicts drought will occur. If the yield reduces, as calculated by MAEM and CEM, we can consider the result of CEM as reliable (referred to as correct number: 1). If the yield reduces as calculated by MAEM but does not as calculated by CEM, we consider the result of CEM as unreliable (correct number: 0). We adapted the Cronbach’s alpha (C_α) coefficient to check the reliability of our method. C_α can be obtained by using the following formula:

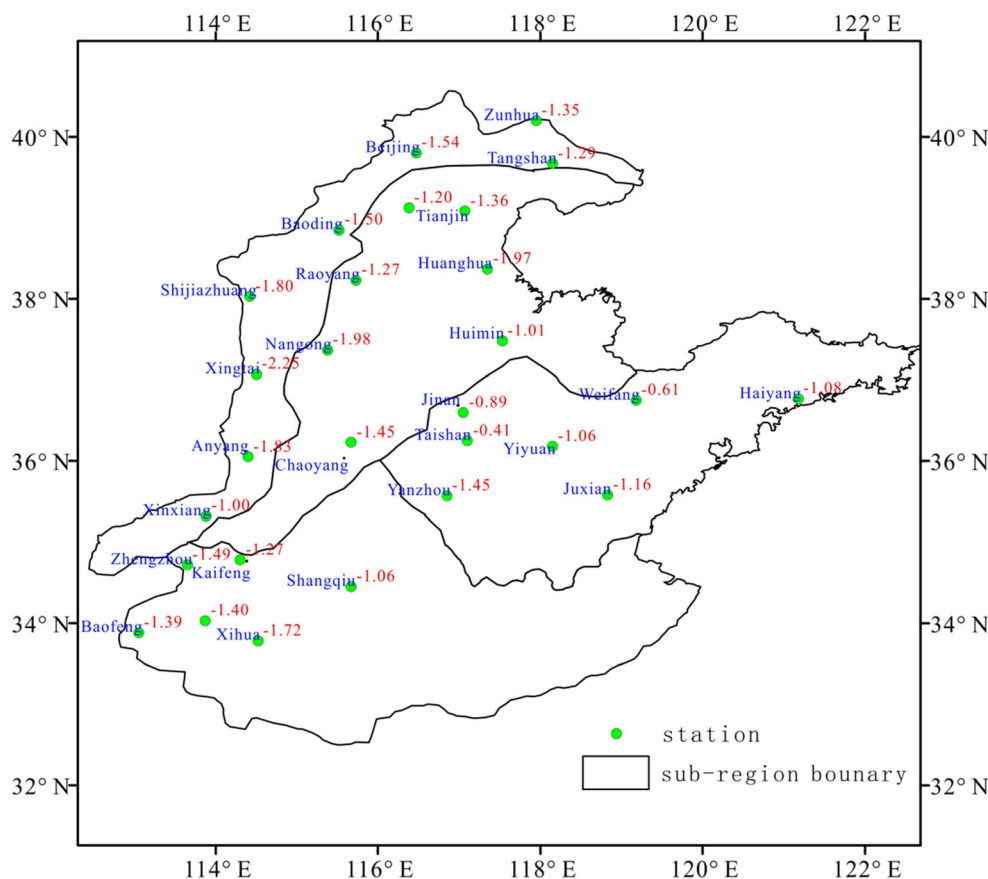
$$C_\alpha = \frac{K}{K-1} \left(1 - \frac{\sum_{i=1}^K \text{var}_i}{\text{var}} \right) \tag{16}$$

Table 5 Correlation between crop yield and water accumulation during growth season (full name of station name in Table 5 may refer to Table 1)

Station name	SPEI_G	SPEI_{G10}	SPEI_{G20}	SPEI_{G30}	SPEI_{G40}	SPEI_{G50}	SPEI_{G60}	SPEI_{G70}	SPEI_{G80}	SPEI_{G90}	SPEI_{G100}
ZH	0.58*	0.66*	0.65*	0.66*	0.67*	0.63*	0.64*	0.55*	0.57*	0.58*	0.61*
BJ	0.69*	0.72*	0.69*	0.70*	0.68*	0.62*	0.63*	0.55*	0.64*	0.63*	0.59*
TS	0.61*	0.63*	0.61*	0.65*	0.67*	0.64*	0.71*	0.72*	0.73*	0.73*	0.70*
LF	0.28	0.45*	0.43	0.51*	0.65*	0.62*	0.71*	0.69*	0.79*	0.80*	0.78*
TJ	0.56*	0.49*	0.52*	0.47*	0.50*	0.47*	0.46*	0.49*	0.48*	0.50*	0.49*
BD	0.74*	0.78*	0.77*	0.78*	0.84*	0.78*	0.75*	0.71*	0.75*	0.73*	0.70*
HH	0.37	0.44*	0.43	0.44*	0.49*	0.45*	0.52*	0.45*	0.58*	0.50*	0.49*
RY	0.68*	0.72*	0.72*	0.74*	0.74*	0.72*	0.68*	0.72*	0.64*	0.74*	0.78*
SJX	0.63*	0.67*	0.68*	0.65*	0.76*	0.78*	0.70*	0.77*	0.79*	0.77*	0.73*
HM	0.65*	0.73*	0.66*	0.67*	0.64*	0.67*	0.50*	0.56*	0.62*	0.66*	0.68*
NG	0.61*	0.60*	0.60*	0.59*	0.57*	0.56*	0.50*	0.57*	0.63*	0.63*	0.69*
XT	0.42	0.45*	0.44*	0.41	0.54*	0.52*	0.53*	0.76*	0.80*	0.80*	0.80*
HY	0.62*	0.62*	0.62*	0.65*	0.64*	0.53*	0.56*	0.54*	0.67*	0.68*	0.67*
WF	0.36	0.43	0.46*	0.44*	0.39	0.42	0.53*	0.54*	0.66*	0.70*	0.67*
JN	0.60*	0.63*	0.60*	0.56*	0.55*	0.61*	0.59*	0.59*	0.70*	0.69*	0.66*
TSH	0.07	0.18	0.18	0.11	0.32	0.32	0.40	0.40	0.40	0.44*	0.51*
YY	0.54*	0.63*	0.60*	0.54*	0.41	0.34	0.37	0.36	0.37	0.43	0.39
AY	0.61*	0.70*	0.58*	0.47*	0.55*	0.54*	0.53*	0.64*	0.74*	0.70*	0.60*
CY	0.59*	0.68*	0.72*	0.65*	0.68*	0.56*	0.48*	0.56*	0.58*	0.64*	0.59*
JX	0.41	0.45	0.50*	0.49*	0.36	0.35	0.37	0.39	0.47*	0.52*	0.49*
YZ	0.30	0.25	0.36	0.41	0.49*	0.51*	0.45	0.45	0.48*	0.46*	0.53*
XX	0.65*	0.64*	0.66*	0.64*	0.59*	0.52*	0.50*	0.49*	0.53*	0.53*	0.39
KF	0.61*	0.68*	0.62*	0.63*	0.71*	0.71*	0.67*	0.76*	0.77*	0.81*	0.74*
ZZ	0.39	0.40	0.48*	0.51*	0.64*	0.67*	0.61*	0.70*	0.72*	0.75*	0.66*
SQ	0.35	0.30	0.47*	0.45*	0.54*	0.49*	0.48*	0.55*	0.68*	0.67*	0.66*
XC	0.34	0.41	0.46*	0.43	0.55*	0.41	0.49*	0.54*	0.56*	0.56*	0.50*
BF	0.31	0.27	0.38	0.33	0.50*	0.41	0.47*	0.56*	0.57*	0.49*	0.48*
XH	0.54*	0.50*	0.54*	0.55*	0.54*	0.55*	0.51*	0.52*	0.64*	0.66*	0.56*
All stations	0.37*	0.39*	0.40*	0.39*	0.42*	0.40*	0.40*	0.42*	0.46*	0.46*	0.44*

Values in italics indicate significance $p > 0.05$, asterisk (*) indicates significance $p < 0.01$, and other values indicates significance $p < 0.05$

Fig. 7 Spatial distribution of SPEI_{G90} at all stations (the red font is value of SPEI_{G90})



where C_α is closer to 1, the result is more reliable, closer to 0, more unreliable. K is the number of drought years to be evaluated. i is the i th drought year. var_i is the variance of correctly evaluated number based on CEM for all province (or municipality) in the i th drought year. var is the variance of correctly evaluated number in each province (or municipality). The classifications for the Cronbach's alpha are shown in Table 4.

Results and discussion

Relationship between yield and multi-time scale SPEI

SPEI_G can represent the water balance conditions including the precipitation and potential evapotranspiration during the whole growing season. However, SPEI_G cannot describe the soil moisture content at the time of crop sowing, which may affect crop growth and yield. The soil moisture content is determined by difference between previous times of precipitation and evapotranspiration because the soil properties were relatively stable. In order to identify how long precipitation and evapotranspiration can affect the soil moisture at the time of sowing the crop, we studied the estimated crop yields and SPEI at different time scales. The SPEI value at different time scales can represent a water balance between precipitation and evapotranspiration

across a period and therefore a specific length of time in which the soil water affects the crop at sowing time.

Based on daily SPEI, the SPEI of multi-time scales were calculated at the 28 stations in the Huang Huai Hai Plain. At each station and in the whole region, we calculated the estimated yield and SPEI of 11 time scales including the times between sowing and harvest, adding 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 days pre-sowing into the growing season of winter wheat (Table 5). SPEI_{G+n} represents the water condition for n days before sowing to harvesting time. SPEI_{G90} is a good indicator of estimated crop yield at each of the stations and across the whole region. There was significant ($p < 0.01$, except 1 station with $p < 0.05$) correlation between SPEI_{G90} and crop yield. Although the correlation coefficient between SPEI_{G80} and crop yield was better than that calculated between SPEI_{G90} and crop yield at eight stations, the correlation coefficient between yield and SPEI of the two time scales were nearly the same. Therefore, the results indicated that SPEI_{G90} had the best correlation to yield at all the stations, and SPEI_{G90} was identified as the best time point to determine SPEI (SPEI_{optimum}). This suggests that the soil moisture at sowing time is affected by the previous 90-day (about 3 months) precipitation and evapotranspiration in the Huang Huai Hai Plain. It also suggests that a 3-month time point for SPEI can represent the soil moisture condition. This conclusion is consistent with a previous study (Seiler et al., 2002).

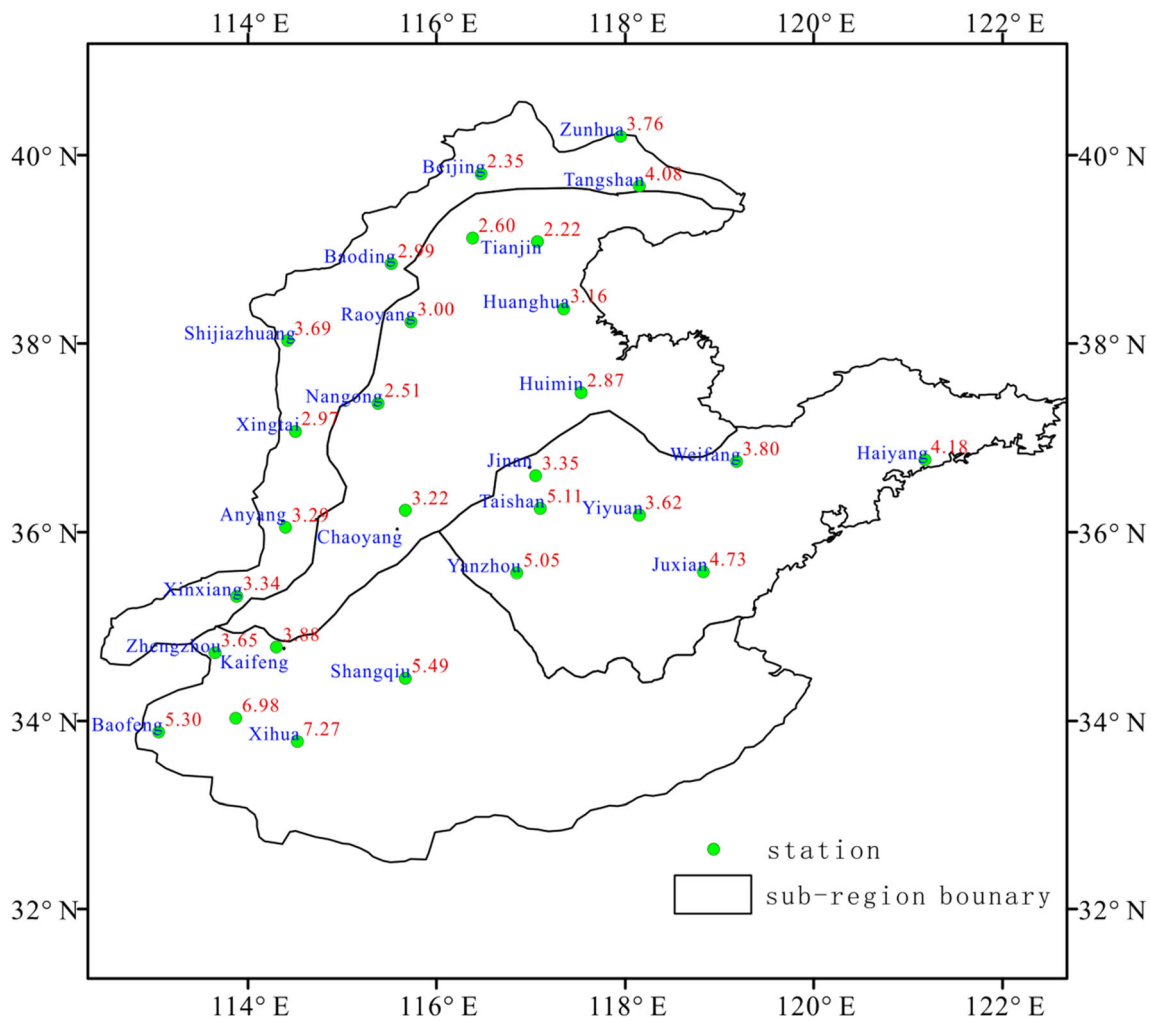


Fig. 8 Spatial distribution of normal yield at all stations (the red font is value of normal yield)

Impact of drought on crop yield

All the stations, except the TSH station (with $SPEI_{G90} = -0.41$), were identified to be in drought in the year 2000 based on the value of $SPEI_{G90}$ (Fig. 7), which illustrated that the water deficit of the winter wheat growing season in 2000 was experienced across the Huang Huai Hai Plain. Therefore, we selected the drought in 2000 to evaluate the impact of drought on crop yield at each of the stations in the Huang Huai Hai Plain. The drought in the west of the region was more severe than in the east, and around the Taishan Mountain the drought was relatively mild, maybe affected by the terrain resulting in a difference of precipitation compared to other regions.

The calculated reference yield (normal yield) based on criteria that identified drought and non-drought years are shown in Fig. 8. Figure 8 illustrates the gradual reduction in crop yield from the southeast to northwest across the whole study area. The precipitation in this region followed the same trend, suggesting that precipitation is the main meteorological factor affecting crop yields.

The reduction rate in crop yield, based on our proposed method, is shown in Fig. 9 which illustrates that the Nangong station had the greatest rate of reduction in crop yield (more than 70 %), with a corresponding $SPEI_{G90}$ of -1.98 (close to extreme drought), and the Xingtai station had the most severe drought, with a $SPEI_{G90}$ of -2.25 and a rate of crop yield reduction of -64.31 %. This suggested that the rate of reduction in crop yield was not always in agreement with the $SPEI_{G90}$, which may be due to water deficits at different stages of growth has different effects on the crop yield (Doorenbos and Kassam, 1979). Wheat growth is the most sensitive to drought during the budding and heading stages, followed by jointing and filling stages (Wang et al., 2001). In conclusion, if $SPEI_{G90}$ is calculated during drought conditions, the crop yield will reduce. Furthermore, if drought conditions occur during the growth season in wheat, the crop yield will decrease but the amount of reduction in yield may be related to the duration of the drought conditions.

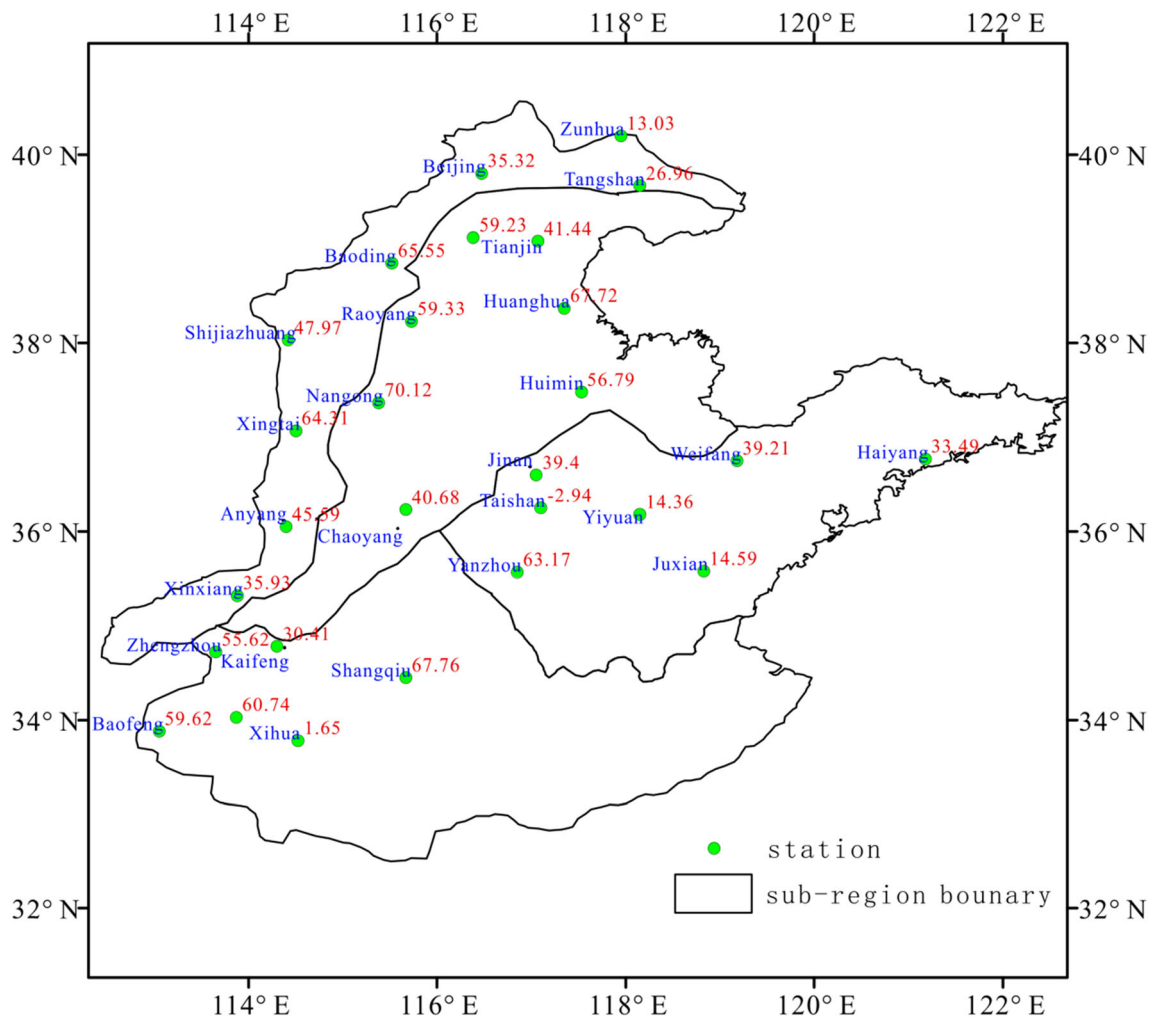


Fig. 9 Spatial distribution of the crop yield reduction rate at all stations (the red font is the value of crop yield reduction rate, unit: %)

Validation of evaluating the impact of drought on crop yield

In our study, we determined whether drought events were responsible for crop yield losses from 1981 to 2010. All crop yield losses in Beijing (six events), Tianjin (four events), and Henan (eight events) occurred while under drought years and were all identified correctly. The number of crop yield losses events in Hebei (seven events) and Shandong (five events) which were correctly identified were six and four, respectively. The reliability index (C_a) was calculated to be 0.90, which indicated a good method. The impact of drought on crop yield based on crop model simulation is very consistent too, with only 1 year in which results did not agree with statistical methods, Shandong Province sub-region in 1981, which had a $SPEI_{G90}$ of -1.04 indicating moderate drought. However, the result using our method is reliable for severe and more severe droughts in all sub-

regions. The reliability index (C_a) of evaluating the effects of severe and more severe droughts for crop yield was 1.

To further test the method described above, a spatial-temporal diagram of $SPEI_{G90}$ and two spatial-temporal diagrams of crop yield losses during drought, based on crop model simulation and statistical method, respectively, were compared and analyzed (Fig. 10). Figure 8 indicates that there were three serious droughts in the years 1981–1982, 2000–2003, and 2007, affecting almost the entire study area. And the drought in 2000–2003 was continuous in time and space. The results of the crop yield losses during drought calculated from the crop model simulation and statistical methods were very consistent especially in severe and extreme drought years, with only one inconsistency in Shandong Province in 1981. This suggests that evaluating crop yield losses occurring during drought based on a crop model simulation is informative.

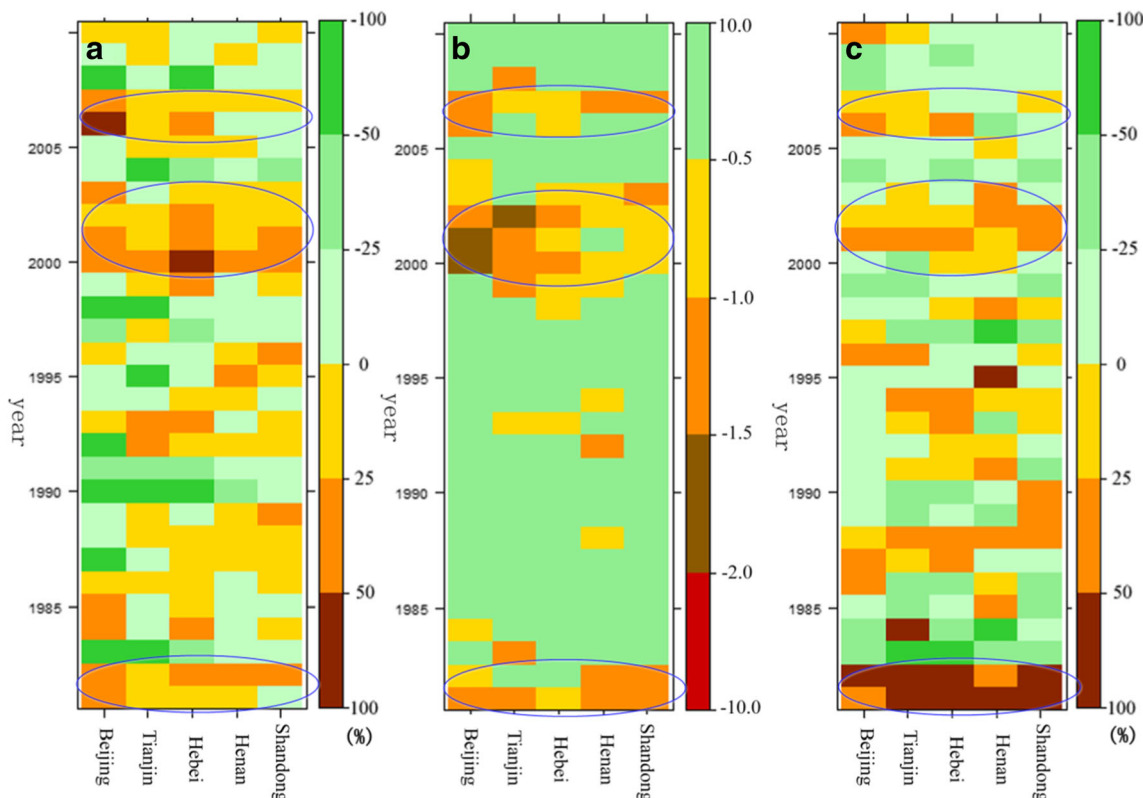


Fig. 10 Spatial-temporal diagram of crop yield reduction rate and $SPEI_{G90}$ (a spatial-temporal diagram of crop yield reduction rate based on our comprehensive evaluating method (CEM); b spatial-temporal

diagram of $SPEI_{G90}$; c spatial-temporal diagram of crop yield reduction rate based on Moving Average Evaluating Method (MAEM), the blue ellipses are three drought events)

Conclusion

The quantitative evaluation of the impact of drought on crop yield is one of the most important challenges of agricultural and water management. Based on studies of crop growth of winter wheat grown under five irrigation regimes at Gucheng in the Huang Huai Hai Plain during 2007–2008, a set of cultivar coefficients of the crop growth model EPIC was calibrated at the Gucheng experimental site, which was used to estimate the crop growth process and crop yield at each station during the years 1980 to 2010. This study investigated the relationships between 11 time scales, daily Standardized Precipitation Evaporation Index (SPEI), and crop yield, based on crop growth model simulation, to determine the optimum time scale SPEI ($SPEI_{optimum}$). $SPEI_{optimum}$ was used to identify the drought and non-drought years for the crop growth period for winter wheat at 28 stations in the Huang Huai Hai Plain (Fig. 9). We propose a new comprehensive quantitative method in evaluating the impact of drought on crop yield by combining the reference yield and estimated yield in a drought year at each station. We also tested our proposed method at provincial (or municipal) level based on the reliability index (C_a).

Our results suggested that the normalized RMSE between estimated and observed yield at 6 stations was 15.4 %, which

indicated EPIC was useful in regional estimation of yield; the soil moisture at sowing time was effected by the previous 90 days (about 3 month) precipitation and evapotranspiration. This study indicated that a length of 90 days, ($SPEI_{G90}$) was the optimum time scale SPEI to identify the drought and non-drought years, and identified the drought year (in 2000). The water deficit of the winter wheat growing season in the year 2000 was serious, with the drought in the west region of the Huang Huai Hai Plain being more severe than in the east. The reference crop yield gradually reduced from the southeast to the northwest of the study area; however, the rate of reduction of crop yield did completely correspond with amount of water deficit. The reliability index indicated that the proposed method is a valid tool for assessing the impact of drought on crop yield.

This study can provide a scientific understanding for the management of drought mitigation strategies on a regional scale. A comprehensive evaluating method which evaluates the impact of drought on crop yield could assist in decision making with regards to resource planning in the Huang Huai Hai Plain. However, it may be more productive to apply this method to multiple crop types to further test the method or expand this method into relevant research fields, such as ecological evaluation and environmental quality evaluation.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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