Postprint: Regional Drought Impact Assessment Technique for Maize Based on the WOFOST Crop Model

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Abstract

To investigate regional drought impact assessment techniques for crops and expand regional impact assessment methods for agrometeorological disasters, this study improved and enhanced modules such as phenological development and photosynthetic production based on the WOFOST crop model, taking drought impacts on corn in Southwest China as the research subject. The model' s suitability was validated using corn field observation data from eight representative stations in Southwest China and concurrent daily meteorological data. On this basis, typical drought years in Southwest China were selected to simulate and analyze corn yield variation trends, which were then compared with actual yield reduction rates. The results indicate that after improvement, the Normalized Root Mean Square Error (NRMSE) between simulated and observed corn phenological stages decreased from 3.25%-6.95% to 1.48%-3.07%, R^2 increased from 0.57-0.79 to 0.63-0.99, and the average simulation accuracy improved from 74.12% to 78.9%. For corn yield, the NRMSE between simulated and observed values decreased from 7.88%-11.99% to 3.07%-6.79%, R^2 increased from 0.52-0.93 to 0.77-0.98, and the average simulation accuracy improved from 75.7% to 80.95%. The average simulation accuracies for yield during critical growth stages in typical drought years (1987, 1992, and 2006) in Southwest China were 69.8%, 78.1%, and 75.9%, respectively. Based on the above analysis, it can be concluded that the model's simulation accuracy for both phenological stages and yield improved to varying degrees, the model demonstrates good responsiveness to drought impact assessment in the main corn-producing regions of Southwest China, and the simulated drought distribution range and patterns are basically consistent with actual conditions, indicating that this method can provide a more scientific assessment technique for regional drought impact evaluation.

Full Text

Evaluation of Regional Drought Disaster Impacts on Maize Using the WOFOST Crop Growth Model

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Abstract: Timely and accurate assessment of drought impacts on maize production in Southwest China has become increasingly important for regional agricultural planning, particularly as drought events grow more frequent and severe under global climate change. To enhance agricultural meteorological disaster assessment methodologies, this study employed the WOFOST crop model to evaluate regional drought impacts on maize, with specific improvements to the phenology and photosynthesis modules. Using field observation data and daily meteorological data from eight representative stations in Southwest China, we validated the model' s suitability. Based on the improved model, we simulated yield variations for historically typical drought years in the region and compared these with actual yield reduction rates. Results showed that after improvement, the normalized root mean square error (NRMSE) between simulated and observed maize phenology decreased from 3.25%-6.95% to 1.48%-3.07%, while R^2 increased from 0.57-0.79 to 0.63-0.99, and average simulation accuracy improved from 74.12% to 78.9%. For maize yield, NRMSE decreased from 7.88%-11.99% to 3.07%-6.79%, R^2 increased from 0.52-0.93 to 0.77-0.98, and average simulation accuracy improved from 75.7% to 80.95%. The average simulation accuracies for yield in the typical drought years of 1987, 1992, and 2006 were 69.8%, 78.1%, and 75.9%, respectively. These results demonstrate that the improvements significantly enhanced simulation accuracy for both phenology and yield, and that the model effectively responds to drought impacts in Southwest China' s major maize-producing regions. The simulated drought distribution patterns and extents closely matched actual conditions, indicating that this approach provides a more scientific assessment technique for regional drought impact evaluation.

Keywords: Crop growth model; WOFOST; Maize; Drought; Phenology; Yield; Simulation precision; Impact assessment

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Agricultural drought represents a global challenge. In recent years, against the backdrop of global warming and increasingly frequent extreme climate events, precipitation and river runoff variability has intensified significantly in Southwest China. Combined with uneven spatiotemporal precipitation distribution, this has led to higher drought frequency and posed substantial threats to regional agricultural production. Timely and accurate assessment of drought impacts on agriculture in Southwest China is therefore crucial for disaster prevention and mitigation. However, agricultural drought impact assessment is complex due to the intricate mechanisms of drought formation and distribution patterns, as well as the inherent complexity of agricultural ecosystems.

Current agricultural drought impact assessment methods primarily include field survey estimation, statistical analysis, remote sensing monitoring, historical analogy analysis, and crop model simulation. Each approach has distinct advantages and limitations, and they are often used individually or in combination. Crop modeling represents a new research field in crop science that applies computer technology and systems analysis to integrate findings from crop physiology, agricultural meteorology, soil science, and agronomy. These models dynamically and quantitatively analyze and simulate crop growth processes as integrated systems of crops and their environmental factors.

International research most frequently reports the application of crop models to agricultural drought assessment, with numerous studies examining drought impacts using various crop models. In China, crop models have gradually been applied to agricultural meteorological disaster assessment. During the Ninth Five-Year Plan period, crop growth models were introduced for winter wheat drought identification and prediction, establishing a soil and crop drought index system for the North China Plain using soil moisture at the beginning of each ten-day period and the water supply-demand ratio. During the Tenth Five-Year Plan period, researchers began developing techniques that combined regional climate models with crop growth models for drought prediction. However, connecting these models introduces cumulative errors, as both individual models contain inherent uncertainties, making this approach's key issues subject to further investigation. Crop models have also seen preliminary application in low-temperature damage assessment.

Despite these advances, crop model applications in agricultural meteorological disasters face challenges. Models require numerous crop parameters, limiting their degree of localization and resulting in insufficient simulation accuracy for phenology and yield, which ultimately affects subsequent assessment applications. To address these limitations, this study improved specific model modules and explored drought impact assessment techniques for maize in Southwest China, aiming to provide a novel method for regional drought impact evaluation.

1.1 Study Area

The study area is located between 98°–110°E and 20°–35°N, encompassing Yunnan Province, Sichuan Province, Guizhou Province, and Chongqing Municipality (collectively referred to as "three provinces and one municipality"). This region features dramatic terrain variations, significant climatic differences, and extremely uneven spatiotemporal precipitation distribution, making it prone to seasonal consecutive droughts and regional drought events. Maize production predominantly occurs in mountainous and semi-mountainous sloping areas under rain-fed dryland farming conditions. The pronounced vertical climate creates substantial variation in agricultural planting zones, with the same crop showing considerable differences in growth periods and development processes at different altitudes. Based on regional characteristics, agroclimatic features, and crop cultivation similarities, the study area' s maize cultivation zones were subdivided into seven sub-regions [Figure 1: see original paper].

1.2 Data Sources

Meteorological data from 61 stations in Yunnan, Guizhou, Sichuan, and Chongqing were used, including daily mean temperature, maximum temperature, minimum temperature, sunshine hours, precipitation, wind speed at 2 m height, and vapor pressure. Concurrent maize phenology and yield data covered 1981-2010, obtained from the Data Office of the National Meteorological Information Center, China Meteorological Administration. Maize phenology data included key developmental stages: sowing, emergence, jointing, tasseling, grain filling, milk ripening, and maturity. Soil data comprised physical properties and fertility characteristics for soils in the four provinces/municipality, including field capacity, wilting coefficient, and bulk density, sourced from provincial/municipal meteorological departments.

1.3 Methods

This study employed the WOFOST crop model to assess drought impacts on maize in Southwest China, with improvements to the phenology and photosynthesis modules. Eight typical representative stations were selected for model suitability validation. Through numerical simulation, yield losses for historically typical drought years were analyzed and compared with actual yield reduction rates.

1.3.1 Crop Model Description The WOFOST (World Food Study) model, developed by de Wit et al. at Wageningen University in the Netherlands, originated from a multidisciplinary research project on global food potential yield organized by the Centre for World Food Studies (CWFS). The model aims to explore possibilities for increasing agricultural productivity in developing countries. WOFOST is a dynamic model that simulates root, stem, leaf, and ear biomass as well as soil moisture based on meteorological and soil conditions. Crop growth processes include development, photosynthesis, respiration, and dry matter accumulation and partitioning. Soil water balance processes encompass precipitation, irrigation, infiltration, surface evaporation, crop transpiration, and capillary rise.

1.3.2 Model Improvements The original WOFOST model has certain limitations, such as its inability to simulate impacts of extreme climate events (high temperature, drought) on crops. Additionally, when foreign crop models are applied domestically, localization may not perfectly match local conditions. Therefore, model improvements are essential to maximize applicability. This study implemented three main improvements: (1) enhanced water stress simulation capability, (2) improved development rate simulation, and (3) refined photosynthetic rate calculation. The water stress improvement used a 10-day moving average of relative transpiration sequences to represent dynamic changes in field water conditions, as detailed in reference [19]. The following sections elaborate on the latter two improvements.

1) Development Rate Improvement

During parameter calibration, the model requires meteorological data from normal years to ensure reasonable and universal parameter determination. However, such ideal data are rarely available in practice, leading to large errors between simulated and observed crop phenology during validation and limiting regional application. To address this issue, we improved the development rate module. The original WOFOST model uses the "accumulated temperature method" to simulate development progress, dividing the entire growth period into two stages: emergence to flowering and flowering to maturity, with effective accumulated temperature for each stage serving as development parameters [20]. The development rate formula is:

(j=1,2) (1)

where r_tD is the development rate at time t (d ¹), e_iT is effective temperature (℃), and $TSUM_j$ is the effective accumulated temperature required to complete a development stage (℃ · d). To enhance the universality of calibrated crop parameters, we introduced a correction coefficient k to improve simulation accuracy:

12 0.5 (0.5 0.15) q = - 1, 0,1) (j=1,2) (2)

where k is the temperature effect coefficient on development rate, calculated as the ratio of crop growth period days in normal years (t_D) to those in disaster years (t'_D): $k > 1$ indicates high-temperature years, while $k < 1$ indicates low-temperature years.

2) Photosynthetic Rate Improvement

Photosynthesis, particularly photosynthetically active radiation, is the fundamental energy source for plant biomass formation, directly affecting growth, development, yield, and product quality. The process converts inorganic matter into organic matter while storing energy, representing the key to crop yield formation. However, crop photosynthesis is highly sensitive to environmental factors, with temperature being a primary influence. In the original WOFOST model, the instantaneous photosynthetic rate at relative canopy height L, LA (kg · hm ² · h ¹), is a function of light-saturated photosynthetic rate mA (kg · hm ² · h ¹) and absorbed radiation I (J · m ² · s ¹), expressed as a negative exponential:

The canopy photosynthetic rate is calculated using Gaussian three-point integration, integrating instantaneous photosynthetic rates of leaves in time and space. The canopy is divided into three layers to calculate instantaneous photosynthetic rates for each layer, which are then weighted to obtain the total canopy instantaneous rate. The day is divided into three points, and the weighted canopy rates at each point are integrated to obtain the daily total photosynthetic rate:

0.15)LAI P = - 1, 0,1) L is the leaf area index at relative canopy position p, where LAI is leaf area index, p is the integration point for canopy height, hA is instantaneous photosynthetic rate for the entire canopy at a given moment, D is day length, q is the integration point for time (day), dA is daily total CO assimilation rate, and hT is daily q moment.

To improve model localization and yield simulation accuracy, we adopted the temperature-photosynthesis relationship from Huang et al. [21] based on laboratory measurements under different temperatures:

TF PO

where TF can be expressed in two cases: ℃ ℃ <℃ ℃, with P and PO representing photosynthetic rates under actual and optimal temperatures, respectively.

1.3.3 Model Suitability Validation Before application, crop models must be calibrated to determine parameters. Detailed calibration procedures and single-point validation methods are provided in references and are not repeated here due to space limitations. Since this study improved the model to address existing problems, we focused on regional suitability validation before and after improvements. Two representative stations were selected from each of the four provinces/municipality (Yunnan, Guizhou, Sichuan, and Chongqing). Considering the large regional differences and pronounced vertical climate in Southwest China, stations were distributed across different altitudes .

Table 1 Maize varieties and years of data for model calibration in Southwest China

Province	Station	Altitude (m)	Variety	Year for validation
Yunnan	Dali	1,990	Huidan 4	1988-1989, 2004-2005
Yunnan	Yuanjiang	400	Haihe 2	1990-1991, 2002-2003
Guizhou	Xingren	1,338	Jinyu 818	1995-1996, 2008-2009
Guizhou	Sinan	416	Zunyi 8	1989, 1995, 2002-2003
Sichuan	Bazhong	358	Xianyu 1171	1993-1994, 2001-2002
Sichuan	Leibo	1,255	Hualongyu 4818	1989-1990, 1998-1999
Chongqing	Shapingba	259	Dingyu 8	1994-1995, 2007-2008
Chongqing	Youyang	720	Dongdan 80	1990-1991, 2003-2004

Model simulation accuracy was evaluated using normalized root mean square error (NRMSE) and coefficient of determination (R^2). NRMSE reflects relative error between simulated and observed values, with smaller values indicating better performance. R^2 reflects consistency between simulated and observed values, with values closer to 1 indicating better performance [22].

2.1 Validation of the Improved WOFOST Model

Figure 2 presents validation results for maize phenology in Southwest China. Before improvement, NRMSE between simulated and observed phenology across eight stations ranged from 3.25%-6.95%, with R^2 values of 0.57–0.79 and average simulation accuracy of 74.12%. After improvement, NRMSE decreased to 1.48%-3.07%, R^2 increased to 0.62–0.99, and simulated values fell near the 1:1 line, with average accuracy improving to 78.9%. This represents a 4.78% improvement in average phenology simulation accuracy.

Figure 3 shows validation results for maize yield at stations with different altitudes. Before improvement, NRMSE for yield ranged from 7.88%-11.99%, with R^2 of 0.52–0.93 and average accuracy of 75.7%. After improvement, NRMSE decreased to 3.07%-6.79%, R^2 increased to 0.77–0.98, and average accuracy improved to 80.95%, representing a 5.25% improvement.

2.2 Simulation Results for Typical Drought Years

Southwest China has experienced several extensive, severe droughts, with typical drought years in each decade being 1969, 1972, 1987, 1992, and 2006 [23]. Due to lack of yield data for 1969 and 1972, we used 1987, 1992, and 2006 for dynamic simulation of drought during maize growth periods. Yield reduction rate was used to characterize drought-induced losses, with results compared against actual yields to validate the model' s capability for simulating agricultural drought impacts. Historical records indicate that the 1987 drought primarily occurred from emergence to jointing, the 1992 drought from emergence to tasseling, and the 2006 drought mainly affected Sichuan-Chongqing regions from jointing to grain filling [24-25].

Simulation results for these typical drought years show that the 1987 drought primarily impacted northern and western Southwest China, with yield reductions of 0.52%–26.49%. Most regions experienced reductions below 10%, with an average regional reduction of 8.02%. Comparison with actual conditions revealed that, except for southern Yunnan, the simulated drought distribution and patterns closely matched reality, with consistent loss severity and simulation accuracy of 69.8%. The 1992 drought mainly affected central-eastern regions, with reductions of 0.65%–31.61% and an average of 11.88%, showing more severe local impacts than 1987. Simulated distribution patterns matched actual conditions well, achieving 78.1% accuracy. The 2006 drought had similar spatial extent to 1992, concentrating in central-eastern regions with reductions of 1.14%–32.9% and a regional average of 9.87%. While model performance was less ideal for severely drought-affected areas due to inherent limitations, the simulated distribution patterns and extents still aligned reasonably well with reality, achieving 75.9% accuracy [Figure 4: see original paper].

3 Conclusions and Discussion

Based on the WOFOST crop growth model with appropriate improvements for the studied disaster type, this study conducted validation analysis at representative stations across different altitudes. Simulations of yield variations during typical drought years in Southwest China showed that the model reproduced drought distribution patterns and extents closely matching actual conditions, demonstrating its capability for assessing drought impacts on regional maize production.

With rapid advances in numerical simulation technology and deeper theoretical understanding of crop disaster mechanisms, crop growth models represent a core component for breakthroughs in agricultural drought monitoring, transitioning from qualitative description to quantitative assessment [26]. The primary advantage of crop models in agricultural meteorological disaster assessment lies in their strong mechanistic basis, effectively reflecting relationships between crop development, yield, and environmental factors including temperature, precipitation, and soil moisture dynamics at each growth stage. However, inherent limitations exist, such as inability to accurately represent drought legacy effects and the need for improved localization.

Based on extensive simulation experiments, this study implemented appropriate model improvements. Validation and simulation results show substantially enhanced simulation accuracy with reduced relative errors between simulated and observed values, greatly improving model reliability. Nevertheless, drought impacts on crops are extremely complex, and substantial uncertainties remain in model boundary conditions and initial parameter values, affecting simulation accuracy. Further research is needed to strengthen and refine these aspects.

Additionally, most crop models are developed and established at field or single-site scales. Scaling up to regional applications involves a point-to-area scaling transformation. In this study, regional model parameters included two types: temperature-related parameters, which were spatially interpolated due to their spatial correlation, and other parameters obtained by refining regions and using representative station parameters for each sub-region [27]. Although model improvements and data processing maximally controlled and reduced errors, the approach still applied the crop model within each homogeneous spatial unit without considering horizontal exchanges of water and nutrients between units, which cannot fundamentally resolve lateral material exchange issues [28]. This aspect requires further investigation.

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Note: Figure translations are in progress. See original paper for figures.