Cloud Model-Based Evaluation Method for Winter Wheat Climate Suitability: A Case Study of Suzhou City, Anhui Province (Postprint)

Authors: Li De, Zhou Wenlin, Yang Feiyun

Date: 2017-11-07T00:00:00+00:00

Abstract

To establish a quantitative evaluation method for winter wheat climate suitability, this study develops cloud models for the effects of sunshine, temperature, and precipitation on wheat growth based on cloud model theory, utilizing threshold indices for light, temperature, and water, and employing the "3En" rule to determine cloud parameters. Weight coefficients are determined using the integral regression method, and climate suitability for different growth stages and the entire growth period is calculated using the weighted comprehensive method and geometric mean method. The models are validated using winter wheat yield per unit area data from various counties (districts) of Suzhou City, Anhui Province from 1954-2013, as well as yield component data from observation plots from 1995-2013. The results indicate that sunshine suitability can be expressed using a left-half cloud, while temperature and precipitation suitability can be expressed using trapezoidal clouds. The calculated climate suitability for the entire winter wheat growth period exhibits significant or highly significant positive correlations with the climate-induced yield of winter wheat in various counties (districts) of Suzhou City; it also shows significant positive correlations with climate-induced yield, thousand-grain weight, grains per spike, and plant height at the milk ripening stage from observation plots, with correlation coefficients of 0.5880 ($P<0.01$), 0.7561 ($P<0.01$), 0.6707 ($P<0.01$), and 0.4643 ($P<0.05$), respectively. The correlation coefficients between climate suitability and spikes per unit area, grains per spike are 0.5589 ($P<0.05$) and 0.7107 ($P<0.01$) for the reviving-jointing stage, and 0.7361 ($P<0.01$) and 0.7442 ($P<0.01$) for the heading-milk ripening stage, respectively; the correlation coefficient between climate suitability and spikes per unit area for the jointing-heading stage is 0.6498 ($P<0.01$). From 1954 to 2013, sunshine and precipitation suitability in Suzhou City decreased at rates of 0.005 and 0.008 per decade, respectively, while temperature suitability increased at a rate of 0.028 per decade. The research findings can serve as a reference basis for evaluating the adaptability of winter wheat to climatic conditions and formulating corresponding strategies in Suzhou.

Full Text

Evaluation of Climate Suitability of Winter Wheat Based on Cloud Model Analysis —A Case Study of Suzhou, Anhui Province

LI De[1], **ZHOU Wenlin**[2], **YANG Feiyun**[3] [1]Suzhou Meteorological Bureau in Anhui Province, Suzhou 234000, China; [2]Hefei Meteorological Bureau in Anhui Province, Hefei 236001, China; [3]China Meteorological Administration Training Center, Beijing 100081, China

Abstract

To establish a quantitative evaluation method for winter wheat climate suitability, this study developed cloud models for sunshine, temperature, and precipitation effects on wheat growth based on cloud model theory, using limiting indexes for light, temperature, and water and employing the "3En" rule to determine cloud parameters. Weight coefficients were determined using integral regression analysis, while weighted comprehensive assessment and geometric mean methods were used to determine climate suitability across different growth stages and the entire growth period. The model was validated using winter wheat yield data from 1954-2013 and observed yield component data from 1995-2013 in Suzhou City, Anhui Province. Results showed that left-half cloud models appropriately expressed sunshine suitability, while trapezoidal cloud models captured temperature and precipitation suitability. Climate suitability during the entire growth period showed significant or highly significant positive correlations with climate-driven yield across Suzhou' s counties and districts, as well as with observed climate yield, thousand-grain weight, kernels per ear, and plant height at the milk stage, with correlation coefficients of 0.5880 ($P<0.01$), 0.7561 ($P<0.01$), 0.6707 ($P<0.01$), and 0.4643 ($P<0.05$), respectively. Correlation coefficients between climate suitability and panicles per unit area were 0.5589 ($P<0.05$) and 0.7361 ($P<0.01$) during the reviving-jointing and heading-milk ripe stages, respectively, while the correlation with kernels per ear reached 0.7107 ($P<0.01$) and 0.7442 ($P<0.01$) for the same periods. The jointing-heading stage suitability showed a correlation of 0.6498 ($P<0.01$) with panicles per unit area. During 1954-2013, sunshine and precipitation suitability decreased at rates of 0.005 and 0.008 per decade, respectively, while temperature suitability increased at 0.028 per decade. These findings provide a scientific reference for evaluating winter wheat adaptability to climatic conditions and developing appropriate response strategies in Suzhou.

Keywords: Winter wheat; Cloud model; '3En' rule; Climate suitability; Climatic yield; Observed yield; Climate factor; Growth period; Suzhou city

1.1 Study Area and Data Sources

Suzhou City in Anhui Province is located in the central Huaibei Plain (33.3°-34.7°N, 116.2°-118.2°E), representing a transitional zone between subtropical and warm temperate climates. The city administers four counties (Si, Lingbi, Xiao, and Dangshan) and Yongqiao District, with a stable winter wheat planting area of approximately 400,000 hectares. Winter wheat is typically sown in mid-to-late October and matures in early June of the following year. During the growth period, the multi-year average precipitation is about 300 mm, accumulated temperature $ $0°C is 2,300°C • d, and sunshine hours are approximately 1,300 h, generally meeting winter wheat growth requirements.

Growth condition data for 1995-2013 were obtained from observation plots at the Suzhou Agrometeorological Experimental Station, located in Yongqiao District with medium fertility level. The planted varieties were ‘Wanmai 19’ from 1995-2009 and ‘Wanmai 52’ from 2010-2013. Observation methods followed the *Observation Specification of Agro-meteorology* [27]. The arithmetic mean dates of winter wheat development stages from 1995-2013 were used as the long-term average dates for Suzhou' s counties and districts (Table 1).

Climate data comprising daily sunshine, temperature, and precipitation measurements from 1954-2013 were collected at national meteorological stations in each county/district. Annual values for each growth stage were calculated as the mean daily temperature and cumulative sunshine hours and precipitation. Following WMO standards, 1981-2010 averages were used as climatic means for each growth stage. Annual yield data for 1954-2013 were obtained from the Suzhou Statistical Bureau' s yearbooks.

1.2.1 Principles of Cloud Model Theory

The cloud model, evolved from probability theory and fuzzy mathematics, effectively characterizes both fuzziness and randomness in event occurrence [20-21]. It is defined as follows: Let Ω be a quantitative domain represented by precise numerical values, and C be a qualitative concept on Ω (i.e., a descriptive linguistic value or index). For any element x in the domain, there exists a stable random number (x) [0,1] called the membership degree of x to C. The distribution of x in domain Ω is called a cloud model, or simply cloud, with each [x, (x)] pair termed a cloud droplet [20].

Cloud models are characterized by three digital features: expectation (Ex), entropy (En), and hyper-entropy (He) [20-21]. Ex represents the cloud' s position in the domain—its center of gravity—and fully belongs to the set. En measures conceptual fuzziness, directly determining the number of domain elements acceptable to a given concept (the margin of “both-this-and-that” ambiguity). He, also called entropy' s entropy, measures the uncertainty of En.

The normal cloud model, developed from normal distribution and bell-shaped membership functions, has demonstrated universal applicability [20-21]. Based on normal clouds, various cloud operations can generate left-half clouds, right-half clouds, and combined clouds. When expectation (Ex) is an interval ($a<x<b$, where a is the lower limit and b the upper limit) where (x) 1, the normal cloud becomes the more general trapezoidal cloud; when $a=b$, the trapezoidal cloud degenerates into a normal cloud. If c is the boundary value of a qualitative concept in the domain, when xc (i.e., domain element x is not greater than c or not less than c) and (x) 1, the normal cloud transforms into a right-half or left-half cloud [20].

Li Deyi et al. [20-21] also provided the normal cloud generation algorithm: (1) Generate a normal random number nE with En as expectation and He^2 as variance; (2) Generate a normal random number xi with Ex as expectation and nE as variance; (3) Let [xi, i(x)] be a cloud droplet with membership degree i(x); (4) Repeat steps 1-3 until N cloud droplets are generated to form the cloud map.

1.2.2 Winter Wheat Climate Suitability Evaluation Method Based on Cloud Model

Light, temperature, and water effects on winter wheat growth exhibit both randomness and fuzziness [1-2]. Randomness manifests as uncertainty when identical climate element values affect different growth stages or when the same element value in different years affects the same growth stage. Fuzziness appears as the difficulty in quantifying the degree of suitability or optimality of climate elements' effects, though such effects exist objectively. Therefore, based on cloud model theory, we define the cloud model of climate conditions' effects on winter wheat growth as follows:

Assume Ω is the domain of possible situations for a climate element in a location, and C is the descriptive value of how that climate element affects winter wheat growth within Ω. For any element value x in domain Ω, there exists a stable random number (x) [0,1] representing the membership degree of climate element value x's effect on winter wheat growth to C. The distribution of climate element x across its possible value domain Ω is called a cloud model, with each [x, (x)] pair termed a cloud droplet, whose distribution exhibits randomness and fuzziness.

Thus, the winter wheat climate suitability evaluation method based on cloud model theory reduces to constructing cloud models for individual climate elements (light, temperature, water). Model construction primarily relies on discrete key indicators of climate element effects on winter wheat growth, such as optimal temperature, maximum/minimum temperatures, and optimal water requirements. Using cloud model parameter construction methods, we determine the cloud model parameters and then drive the model with measured or forecasted climate element values to obtain membership degrees of climate element effects on winter wheat growth. Based on membership degree magnitude, we achieve quantitative evaluation of climate condition suitability for winter wheat growth and development.

For data without certainty information (i.e., without constraints) such as annual precipitation or evapotranspiration, the backward normal cloud algorithm [20-21] can be used to obtain the three digital features of the cloud model. For problems with certainty (i.e., with constraints), such as when sunshine hours exceed a certain threshold or temperature/precipitation falls within a specific range where suitability is maximized, the three parameters are generally determined as follows: Ex takes the constrained descriptive value or threshold [21,26]; En follows the "3En" rule [20-21], taking one-third of the distance from Ex to the upper (a) or lower (b) limit [20,28], i.e., En=(Ex−a)/3 for left-half clouds and En=(b−Ex)/3 for right-half clouds; He is generally determined empirically based on value fluctuations [21,26].

1.2.3 Climate Suitability During Different Winter Wheat Growth Stages

During winter wheat growth, sunshine suitability [(S)], temperature suitability (T), and precipitation suitability (R) in a given stage interact to determine the climate suitability for that stage [2,29]:

S,T,R

where j(S,T,R) is the climate suitability of winter wheat at growth stage j, and j(S), j(T), j(R) are the sunshine, temperature, and precipitation suitability at stage j, respectively.

1.2.4 Climate Suitability During Whole Winter Wheat Growth Period

Different growth stages have distinct physiological and ecological characteristics with varying climate requirements, and climate factors affect winter wheat growth and yield formation differently across stages. To objectively reflect the influence intensity of climate factors at different stages when calculating whole-growth-period suitability, weight coefficients must be assigned to each stage' s climate suitability. This study used the weighted method [19] to determine whole-growth-period climate suitability. Weight coefficients were determined using unary integral regression analysis: integral effect coefficients (asj, atj, arj) of sunshine hours, temperature, and precipitation for each growth stage on winter wheat yield were calculated, and the absolute value of each coefficient was divided by the sum of absolute values of all stages' coefficients to obtain weight coefficients for each stage' s sunshine, temperature, and precipitation suitability. Multiplying each element' s membership degree by its corresponding weight coefficient and summing yields the whole-growth-period sunshine hours, temperature, and precipitation suitability:

(3)

where bsj, btj, brj are weight coefficients for sunshine hours, temperature, and precipitation membership degrees at stage j, and (S), (T), (R) are the whole-growth-period sunshine hours, temperature, and precipitation suitability, respectively.

Following formula (2), the geometric mean method was used to obtain whole-growth-period climate suitability:

1.3 Model Validation and Application

To test whether the established winter wheat climate suitability cloud model could objectively reflect climate condition effects on crop growth, annual yield data from 1954-2013 for Yongqiao District and the four counties were decomposed into trend yield (driven by socioeconomic factors) and climate yield (driven by climate factors). Orthogonal polynomials combined with 3-year moving averages were used to fit trend yield, which was compared with actual yield to obtain climate yield for 1954-2013. Climate yield was normally distributed. Using meteorological data from national stations for 1954-2013, annual winter wheat climate suitability was calculated for each county/district and correlated with corresponding climate yield.

Additionally, using 1995-2013 data from the Suzhou Agrometeorological Experimental Station—including plot yield ($\text{kg}\cdot\text{hm}^{-2}$), thousand-grain weight (g), kernel weight per ear (g), panicles per unit area (\$$\times10^{\{4\}\cdot hm}${-2}\$), and plant height at milk stage (cm)—relationships with climate suitability were analyzed to test the model's explanatory power for key growth elements. Yield component and plant height measurements followed standard methods [27].

2.1 Sunshine Suitability Cloud Model

The effect of sunshine conditions on winter wheat growth transitions from "unsuitable" to "suitable" as sunshine hours increase, with the critical value representing optimal sunshine duration. Through long-term cultivation and breeding, crops develop strong ecological adaptability to local sunshine conditions [30-31], and climatic mean sunshine hours reflect the average state of sunshine conditions over time. Therefore, this study used climatic mean sunshine hours during each growth stage as the critical value for maximum sunshine suitability. Table 2 shows climatic mean sunshine hours for different growth stages in Yongqiao District.

Generally, when sunshine hours exceed the critical value, sunshine suitability [(x)] is maximized ((x) 1). Below the critical value, insufficient light affects normal growth, and suitability decreases proportionally—more severely as values fall further below the climatic mean, eventually decaying to (x)=0. This decay process exhibits obvious randomness and fuzziness, making the left-half cloud model appropriate for expressing sunshine suitability.

Following the methods in Section 1.2, cloud model parameters for sunshine suitability were obtained for different growth stages in Yongqiao District (Table 3). Using MATLAB and the backward cloud generation method [20] with 500 cloud droplets, sunshine suitability cloud models [j(S)] were generated for each growth stage (Figure 1 [Figure 1: see original paper]), where j=1,2,⋯,7 corresponds to the seven growth stages in Table 1.

Figure 1 and Table 3 show that different growth stages have different sunshine critical values, resulting in varying Ex values. When sunshine hours are below Ex, the membership degree (cloud droplets) exhibits an atomized state, effectively characterizing the uncertainty of sunshine effects on wheat growth below critical values—unlike traditional smooth membership function curves [10-13] that only reflect deterministic relationships.

Using formula (1), when sunshine hours (x) for a growth stage are known, a set of cloud droplets [x, (x)] can be simulated, meaning the same sunshine hours generate random cloud droplets in the model, or the same variable x can randomly produce different membership degrees (x). When calculating cloud droplets from 1954-2013 sunshine data for each county/district, the average of five membership degrees was used as the sunshine suitability for each year and growth stage:

 j(S) = (1/5) i(x) (5)

where i=1,2,⋯,5 represents the number of cloud droplets [x, (x)].

2.2 Temperature Suitability Cloud Model

Winter wheat has different temperature requirements across growth stages, with minimum, maximum, and optimal temperatures—the latter often having a certain range [10,31]. Within the optimal range, wheat grows well and temperature suitability [(x)] is maximized ((x) 1). Below the optimal lower limit down to the multi-year mean minimum temperature, or above the optimal upper limit up to the multi-year mean maximum temperature, suitability decreases with randomness and fuzziness. Therefore, temperature effects exhibit trapezoidal cloud characteristics [20], which this study adopted. Integrating previous research [10-11,13] with Suzhou' s agrometeorological service experience, minimum, maximum, and optimal temperature indicators were determined for each growth stage (Table 4).

Following Section 1.2 methods, temperature suitability cloud model parameters were obtained for different growth stages in Yongqiao District (Table 5). Using MATLAB with the backward cloud generation method and 500 cloud droplets, temperature suitability cloud models [j(T)] were generated for each growth stage (Figure 2 [Figure 2: see original paper]).

Figure 2 shows that when temperature is within the suitable range, membership degree equals 1. Outside suitable boundary temperatures, membership decays in an atomized state, with suitability decreasing to 0—consistent with the biological 规律 of temperature effects on wheat growth. Similarly, using formula (1) with

1954-2013 temperature data, five cloud droplets were generated for each year and growth stage, with their mean used as temperature suitability [j(T)].

2.3 Precipitation Suitability Cloud Model

Different crops or varieties have varying water requirements across growth stages. Following Hou Yingyu et al. [2], water requirement (ETp) for a growth stage refers to crop evapotranspiration under optimal soil moisture and fertility conditions, with normal field development, no disease, and high yield levels. ETp is calculated as:

$ETp = ET_0 \times Kc$

where ET_0 is reference crop evapotranspiration, calculated using the FAO-recommended Penman-Monteith model (1998 version) [32-33], and Kc is the crop coefficient for the corresponding period, obtained from literature [34-37] (Table 6).

The Huaibei Plain is a rain-fed winter wheat region where atmospheric precipitation is the primary water source [6,35,37]. Both excessive and insufficient precipitation adversely affect winter wheat growth, meaning there is an optimal precipitation range. Within this range, wheat develops well and climate suitability reaches maximum. Outside the lower or upper limits, precipitation suitability decreases. Therefore, precipitation effects can be characterized using trapezoidal clouds similar to temperature.

Using literature [19] and considering Huaibei Plain climate characteristics, precipitation (R) satisfying 0.65ETp≤R\$ $1.20ETpmaximizedclimatesuitability(\mu(x) \equiv 1)beforejointingandafterjointing.Duringreviving–jointingstage, 0.75ETp\ R$ \$1.50ETp maximized suitability. When R<0.65ETp or <0.75ETp, or R>1.20ETp or >1.50ETp, precipitation adversely affected wheat growth and suitability decreased to 0. R=0.65ETp or 0.75ETp and R=1.20ETp or 1.50ETp served as lower and upper limits of optimal precipitation, while zero precipitation and the maximum precipitation during 1960-2013 were used as boundary values (Table 7).

Following Section 1.2 methods, precipitation suitability cloud model parameters were obtained for different growth stages in Yongqiao District (Table 8). Using MATLAB with the backward cloud generation method and 500 cloud droplets, precipitation suitability cloud models [j(R)] were generated for each growth stage (Figure 3 [Figure 3: see original paper]).

Figure 3 shows that when precipitation is within the suitable range, membership degree equals 1. Outside suitable boundary precipitation, membership decays atomically to 0, consistent with biological 规律. Notably, for seeding-trileaf and milk ripe-maturity stages, the left-half cloud decays more rapidly than the right-half cloud, indicating that insufficient precipitation has greater adverse effects than excess precipitation—an important consideration for wheat production in Suzhou.

Similarly, using formula (1) with 1954-2013 precipitation data, five cloud droplets were generated for each year and growth stage, with their mean used as precipitation suitability j(R).

2.4.1 Changes in Light, Temperature, and Water Suitability During Whole Growth Period

Averaging climate suitability values from 1954-2013 for Yongqiao District and the four counties yielded annual climate suitability for Suzhou City (Figure 4 [Figure 4: see original paper]).

Figure 4 shows that during 1954-2013, sunshine and temperature suitability were highest, with averages above 0.9, while precipitation suitability was lowest, averaging below 0.6 with much greater interannual variability. This indicates that light and heat resources generally meet winter wheat requirements, but precipitation is the limiting factor for yield formation. Statistical analysis revealed decreasing trends for sunshine and precipitation suitability at rates of 0.005 and 0.008 per decade, respectively, while temperature suitability increased at 0.028 per decade (significant at $P<0.01$), suggesting increasing positive effects of temperature and increasing negative effects of precipitation and sunshine on winter wheat growth in Suzhou.

2.4.2 Characteristics of Climate Suitability Changes During Whole Growth Period

Figure 5 [Figure 5: see original paper] shows interannual variation and trends in whole-growth-period climate suitability for Suzhou winter wheat. During 1954-2013, climate suitability averaged around 0.7 but showed an overall increasing trend of 0.002 per decade. Interannual variation was large during 1954-1960. From 1960-1975, large fluctuations continued, except for 1990-1994 when suitability remained above 0.7 for five consecutive years. After 2003, climate suitability generally decreased, indicating that under global climate change, negative climate effects on winter wheat growth in Suzhou are increasing, raising climate risks for regional wheat production.

2.5 Relationship Between Climate Suitability and Climate Yield

Using the established method and cloud model parameters, winter wheat climate suitability was calculated for Yongqiao District and the four counties, and correlated with corresponding climate yields ($n=60$). Results showed significant positive correlations between climate suitability and climate yield, with correlation coefficients of 0.3141 ($P<0.05$), 0.3327 ($P<0.01$), 0.3211 ($P<0.05$), 0.2732 ($P<0.05$), and 0.3327 ($P<0.01$) for Yongqiao, Si, Lingbi, Xiao, and Dangshan counties, respectively. Counties with weaker irrigation conditions (Si and Dangshan) showed the strongest correlations ($P<0.01$), demonstrating that the climate suitability model objectively reflects climate suitability levels and their dynamics for winter wheat in Suzhou.

2.6 Relationship Between Climate Suitability and Yield Components

Using 1995-2013 observation data from the Suzhou Agrometeorological Experimental Station, relationships between climate suitability and plot yield, panicles per unit area, kernels per ear, kernel weight per ear, thousand-grain weight, and plant height at milk stage were analyzed. Plot yield was separated into trend and climate yields using orthogonal polynomials. Correlations between whole-growth-period climate suitability and climate yield, thousand-grain weight, kernels per ear, and plant height were significant or highly significant (Figure 6 [Figure 6: see original paper]), with correlation coefficients of 0.5880 ($P<0.01$), 0.7561 ($P<0.01$), 0.6707 ($P<0.01$), and 0.4643 ($P<0.05$), respectively. This indicates strong explanatory power: higher climate suitability corresponds to higher yield, greater thousand-grain weight, and more kernels per ear.

Regression equations between whole-growth-period suitability and each parameter (Figure 6) were all significant at $P<0.01$, enabling yield component estimation from growth-stage climate suitability for growth assessment. Since different yield components form during different stages with varying climate requirements, relationships were tested between climate suitability during key periods (reviving-jointing, jointing-heading, heading-milk ripe) and panicles per unit area, kernels per ear, and kernel weight per ear. All correlations were significant or highly significant: reviving-jointing suitability correlated with panicles per unit area and kernels per ear at 0.5589 ($P<0.05$) and 0.7107 ($P<0.01$); jointing-heading suitability correlated with panicles per unit area at 0.6498 ($P<0.01$); heading-milk ripe suitability correlated with panicles per unit area and kernels per ear at 0.7361 ($P<0.01$) and 0.7442 ($P<0.01$). As growth stages become more refined, positive correlations between climate suitability and target yield components increase, further demonstrating the model’ s strong explanatory power for climate effects on winter wheat growth.

Conclusions

1) Based on cloud model theory, this study established left-half cloud models for sunshine suitability and trapezoidal cloud models for temperature and precipitation suitability. The models have clear biological meaning and account for both randomness and fuzziness in climate effects on crop growth. Statistical tests showed significant positive correlations between calculated climate suitability and winter wheat yield and its components, passing significance ($P<0.05$) or high significance ($P<0.01$) tests. Climate suitability during key growth stages showed significant positive correlations with target yield components, particularly heading-milk ripe suitability with panicles per plant and kernels per ear ($r=0.7361$, $P<0.01$ and $r=0.7442$, $P<0.01$). The models can effectively evaluate climate condition suitability for winter wheat growth.

2) During 1954-2013, climate suitability of individual elements showed obvious interannual variation, especially precipitation suitability (average

<0.6) compared to sunshine and temperature suitability (>0.9). Sunshine and precipitation suitability decreased at 0.005 and 0.008 per decade, respectively, while temperature suitability increased at 0.028 per decade. However, since 2003, comprehensive climate suitability has decreased, indicating increasing negative climate effects on winter wheat growth in Suzhou—consistent with patterns in Henan and Hebei provinces within the same Huang-Huai winter wheat region [11,19,39].

3) Model construction used sunshine, temperature, and precipitation indicators obtained from literature and Suzhou' s meteorological service experience. The sunshine critical indicator was determined based on the ecological principle that crops develop strong adaptability to local conditions through long-term cultivation [30-31], differing from literature using 70% of possible sunshine hours [10-11] and better reflecting crop adaptation. This represents an innovation of this study. However, the precipitation indicator, though considering dynamic water requirements through weight coefficients, did not account for precipitation after-effects and effectiveness [2], representing a limitation for future improvement.

4) No complete theory currently exists to scientifically determine En for converting qualitative concept values to cloud parameters [20]. This study combined experience with the "3En" rule [20-21] to determine parameters. More objective determination of En and He will be a future focus. Additionally, the climate suitability evaluation cloud model was developed for Huaibei Plain climate characteristics and related indicators; regional adaptation should be considered when applying elsewhere.

References

[1] Luo H L, Chen G J, Zhu B. Review on suitability of agro-climate[J]. Journal of China Agricultural Resources and Regional Planning, 2004, 25(1): 28-32

[2] Hou Y Y, Zhang Y H, Wang L Y, et al. Climatic suitability model for spring maize in Northeast China[J]. Chinese Journal of Applied Ecology, 2013, 24(11): 3207-3212

[3] Tao F L, Yokozawa M, Xu Y L, et al. Climate changes and trends in phenology and yields of field crops in China, 1981-2000[J]. Agricultural and Forest Meteorology, 2006, 138(1/4): 82-92

[4] Liu Z J, Yang X G, Wang W F, et al. Characteristics of agricultural climate resources in three provinces of Northeast China under global climate change[J]. Chinese Journal of Applied Ecology, 2009, 20(9): 2199-2206

[5] Xie L Y, Li Y, Xu Y X, et al. Updated understanding on the impacts of climate change on food production and food security[J]. Progressus Inquisitiones de Mutatione Climatis, 2014, 10(4): 235-239

[6] Ma X Q, Zhang H Q, Wu W Y, et al. Analyzing and zoning of the eco-climate

suitability on winter wheat varieties in Anhui Province[J]. Chinese Journal of Agrometeorology, 2012, 33(1): 86-92

[7] Li D, Yang T M, Liu R N, et al. Low temperature risk division in winter for protected agriculture in Anhui Province[J]. Chinese Journal of Agrometeorology, 2013, 34(6): 703-709

[8] Gu H Y, Ai N S. The dynamic models of agro-climate system[J]. Discovery of Nature, 1984(1): 43-56

[9] Xu H, Li B H. Analysis of agro-ecolmate resources in Shandong Province with suitability degree[J]. Journal of Shandong Normal University: Natural Sciences Edition, 1993, 8(4): 41-46

[10] Huang H. A study on the climatic ecology adaptability of the crop production in the red and yellow soils region of China[J]. Journal of Natural Resources, 1996, 11(4): 340-346

[11] Zhao F, Qian H S, Jiao S X. Climatic suitability model of crop: A case study of winter wheat in Henan Province[J]. Resources Science, 2003, 25(6): 77-82

[12] Ren Y Y, Qian H S. Climatic suitability of cotton and its changes in Henan Province[J]. Journal of Applied Meteorological Science, 2006, 17(1): 87-93

[13] Wei R J, Song Y B, Wang X. Method for dynamic forecast of corn yield based on climatic suitability[J]. Journal of Applied Meteorological Science, 2009, 20(5): 622-627

[14] Yi X, Wang J L, Song Y B. Application of climatic suitability index to dynamical prediction of early rice yield[J]. Meteorological Monthly, 2010, 36(6): 85-89

[15] Li H Y, Wang J L, Zheng C L, et al. The development period prediction of winter wheat based on climatic suitability in North China[J]. Meteorological Monthly, 2012, 38(12): 1554-1559

[16] Ma X X, Deng Z Y, Li D L, et al. Study on eco-climate applicability of spring wheat for condign planting division in Gansu Province[J]. Journal of Applied Meteorological Science, 2005, 16(6): 820-827

[17] Yao X Y, Pu J Y, Yao R X, et al. Variation of climate suitability of maize in arid area in Gansu under the condition of climate dry-warming[J]. Acta Geographica Sinica, 2011, 66(1): 59-67

[18] Duan H L, Qian H S, Li M X, et al. Climatic suitability of citrus in subtropical China[J]. Chinese Journal of Applied Ecology, 2010, 21(8): 1915-1925

[19] Wei R J, Zhang W Z, Kang X Y, et al. Application and establishment of climatic suitability dynamic model of winter wheat in Hebei Province[J]. Agricultural Research in the Arid Areas, 2007, 25(6): 5-9

[20] Li D Y, Du Y. Artificial Intelligent with Uncertainty[M]. Beijing: National Defence Industry Press, 2005: 131-165

[21] Liu C Y, Li D Y, Pan L L. Uncertain knowledge representation based on cloud model[J]. Computer Engineering and Applications, 2004, 40(2): 32-35

[22] Li G, Wan Y C. Uncertainty classification method of remote sensing image based on high-dimensional cloud model and RBF neural network[J]. Science of Surveying Mapping, 2012, 37(1): 115-118

[23] Zhang Y, Yan J M, Jiang P, et al. Normal cloud model based evaluation of land resources ecological security in Hubei Province[J]. Transactions of the Chinese Society of Agricultural Engineering, 2013, 29(22): 252-258

[24] Sun H H, Cheng X F, Ni L, et al. Capacity evaluation of flood disaster prevention and reduction in Chaohu Basin based on cloud model and entropy weight method[J]. Journal of Catastrophology, 2015, 30(1): 222-227

[25] Zhang Q W, Zhang Y Z, Zhong M. A cloud model based approach for multi-hierarchy fuzzy comprehensive evaluation of reservoir-induced seismic risk[J]. Journal of Hydraulic Engineering, 2014, 45(1): 87-95

[26] Li D, Yang F Y, Sun Y, et al. Meteorological suitability evaluation based on cloud model for spraying pesticide/fertilizer in wheat fields of Huaibei Plain[J]. Chinese Journal of Ecology, 2016, 35(1): 259-268

[27] China Meteorological Administration. Observation Specification of Agro-meteorology[M]. Beijing: China Meteorological Press, 1993: 10-31

[28] Zhang G Y, Sha Y, Liu X H, et al. High dimensional cloud model and its application in multiple attribute evaluation[J]. Transactions of Beijing Institute of Technology, 2004, 24(12): 1065-1069

[29] Ma S Q. Agro-climate Research in Jilin Province[M]. Beijing: China Meteorological Press, 1994: 33

[30] Han X L. Crop Ecology[M]. Beijing: China Meteorological Press, 1991: 15-18

[31] Gong S X. Crop and Meteorology[M]. Beijing: Agriculture University Press, 1987: 35-45

[32] Allen R G, Smith M, Pereira L S, et al. An update for the calculation of reference evapotranspiration[J]. ICID Bulletin, 1994, 43(2): 35-92

[33] Liu Y, Pereira L S, Teixeira J L, et al. Update definition and computation of reference evapotranspiration comparison with former method[J]. Journal of Hydraulic Engineering, 1997(6): 27-33

[34] Chen X Y, Ma X Q, Sun X B. Risk analysis of agricultural drought for winter wheat during growing period in Anhui Province[J]. Chinese Journal of Agrometeorology, 2008, 29(4): 472-476

[35] Ma X Q, Yao Y, Xu Y. A model for dynamic assessment of crop yield losses from drought and its tryout in Anhui Province[J]. Journal of Catastrophology, 2010, 25(1): 13-17

[36] Ding D J, Zhang X H. A preliminary study on water requirement of major crops in Huaibei area of Jiangsu Province[J]. Resources Science, 1994(3): 40-46

[37] Wang X D, Ma X Q, Xu Y, et al. Temporal analysis of the crop water surplus deficit index for the whole growth period in the Huaihe Basin[J]. Resources Science, 2013, 35(3): 665-672

[38] Hu C L. Anhui Wheat Crop Cultivation[M]. Hefei: Anhui Science and Technology Press, 2009: 1-14

[39] Qian H S, Jiao S X, Zhao F. Climate suitability change of winter wheat in Henan Province[J]. Chinese Journal of Ecology, 2005, 24(5): 503-507

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

Source: ChinaXiv —Machine translation. Verify with original.