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Crop Science/ Original Article

Modeling the yield of winter maize using biomass distribution index in the tropical region of Yunnan, China

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Abstract – The objective of this work was to establish and validate the dry matter distribution and yield prediction models based on physiological developmental timing, to compare the differences between the dry mass distribution index model and the dry mass distribution coefficient model, for the simulation of ear dry mass and to improve the accuracy of maize growth models for predicting yield. The experiments were conducted in three tropical sites (Longchuan, Mangshi, and Ruili) in the tropical region of Yunnan Province, China. The NRMS of ear dry mass and yield were generally less than 10. The dry mass distribution index method (NRMS = 5.44% and RMSE = 807.22 kg ha^{-1} for ear dry mass; and NRMS = 7.32% and RMSE = 707.67 kg ha^{-1} for grain yield) is better than the dry mass distribution coefficient method (NRMS = 7.52% and RMSE = 1115.31 kg ha^{-1} for ear dry mass; NRMS = 8.6% and RMSE = 830.76 kgha^{-1} for grain yield) to simulate maize ear dry mass and grain yield. The distribution index model improves the accuracy of the model, which is valuable for future maize production and management in Yunnan.

Index terms: *Zea mays*, dry mass, grain yield, simulation model.

Modelagem do rendimento do milho de inverno por meio do índice de distribuição de biomassa na região tropical de Yunnan, China

Resumo – O objetivo deste trabalho foi estabelecer e validar um modelo de previsão de distribuição de massa de matéria seca e de rendimento, com base no tempo de desenvolvimento fisiológico, para comparar as diferenças entre o modelo de índice de distribuição de matéria seca e o modelo de coeficiente de distribuição de matéria seca, para a simulação da massa de matéria seca da espiga e para melhorar a precisão de modelos de crescimento do milho para a previsão de rendimento. Os experimentos foram realizados em três locais (Longchuan, Mangshi e Ruili), na região tropical da província de Yunnan, China. O NRMS da massa de matéria seca e o rendimento da espiga foram geralmente menores que 10. O método do índice de distribuição da massa de matéria seca (NRMS = 5,44% e RMSE = 807,22 kg ha^{-1} para massa de matéria seca da espiga; e o NRMS = 7,32% e RMSE = 707,67 kg ha^{-1} para rendimento de grãos) é melhor do que o método do coeficiente de distribuição de massa de matéria seca (NRMS = 7,52% e RMSE = 1115,31 kg ha^{-1} para massa de matéria seca de espiga; NRMS = 8,6% e RMSE = 830,76 kg ha^{-1} para rendimento de grãos) para a simulação da massa de matéria seca de espiga e o rendimento de grãos de milho. O modelo do índice de distribuição melhora a precisão do modelo, o que é valioso para o futura produção de milho e seu manejo em Yunnan.

Termos para indexação: *Zea mays*, massa de matéria seca, rendimento de grãos, modelos de simulação.

Introduction

Maize (*Zea mays* L.) is one of the most important food crops in the world, accounting for 36.8% of the annual grain sown in China (43.32 million) in 2021 (Zeng, 2022). Winter-sown maize is essential to agricultural production and accounts for a significant portion of farmers' household income, making it one of the most essential cash crops. The crop growth model is a tool for describing the inner law of crop growth and development based on the crop growth process, dry mass accumulation, and yield formation, by integrating the research findings of crop physiology, meteorology, ecology, water fertilization, soil, and agronomy, using computer technology and mathematical methods (Cai et al., 2021). The development of a model for the accumulation and distribution of dry mass in maize is an essential tool for quantitatively analyzing the dynamic growth process of maize. It is capable of systematically analyzing and summarizing the growth situation of maize, offering theoretical guidance for its optimal management.

The research on maize growth simulation is relatively mature, and more applications such as CERES-Maize, WOFOST, EPIC, APSIM-Maize, etc. are currently available (Rugira et al., 2021; Amiri et al., 2022; Di Bene et al., 2022; Wang et al., 2023). The model can accurately predict the maize development, morphogenesis, biomass accumulation, distribution, and yield formation processes, with dry mass accumulation and distribution serving as the core module of the model. The accumulation and distribution of dry mass is a complex physiological-ecological process. It is affected by numerous variables, including climate, varieties, management practices, and planting techniques (Levis et al., 2018). The accumulation of dry mass in maize is the basis for seed formation and, in conjunction with dry mass distribution, it determines yield (Elmore et al., 2019). Theories such as the functional equilibrium (Friedlingstein et al., 1999), the optimal control (Cohen, 1971), and the source-sink relationship (Ping et al., 2010) are commonly applied premise-hypotheses to model the dry mass distribution in crops (Contreras et al., 2013; Tan et al., 2019). The simulation of crop dry mass distribution processes is confined by dry mass distribution models based on a single theoretical hypothesis. Subsequently, a variety of simulation methods for predicting dry mass distribution were developed, among which the dry mass distribution coefficient method and the dry mass distribution index are the most extensively used. By leveraging the dry mass distribution coefficient method, a model of the dry mass dynamics of summer maize in northern China was developed, and the dynamics of the dry mass distribution were investigated for maize leaves, stems, and ears (Li et al., 2016).

There are variations in the simulation effects of dry mass distribution, despite the relatively advanced simulation studies on maize growth and yield formation. Moreover, fewer studies have compared the dry mass distribution coefficient method and the distribution index method.

The objective of this work was to establish and validate the dry matter distribution and yield prediction models based on physiological developmental timing, to compare the differences between the dry mass distribution index model and the dry mass distribution coefficient model, for the simulation of ear dry mass and to improve the accuracy of maize growth models for predicting yield.

Materials and Methods

A field experiment was conducted in Longchuan (24°2'N, 97°79'E), Mangshi (24°4'N, 98°59'E), and Ruili (24°1'N, 97°85'E), located in the southern part of Yunnan Province, China, which is the main planting area of winter sowing maize. The average annual temperature in the whole area is 18–21°C, the average annual precipitation is 1,400–1,700 mm, and the sunshine duration is 2,281–2,453 hours. The soil from the experimental area is classified as a Ferralsol (IUSS Working Group WRB, 2015).

The meteorological data of each meteorological station were obtained from The Yunnan Meteorological Bureau, including the daily maximum and minimum temperatures, and the number of sunshine hours. The Penman-Monteith formula was used to calculate the total solar radiation value required by the model.

Crop data were obtained from the field experiments in Longchuan and Ruili in 2010–2012, and Mangshi in 2017–2018. Sowings were performed in the following periods: two at the Ruili site, in 2010 (7 December and 28 December); two at the Longchuan site, in 2010 (18 December and 29 December); and two at the Mangshi site, in 2017 (14 December and 4 January). All harvestings were carried out in June of the following years. The sowed maize cultivars were Huidan 4 (HD4) and Deyu 6 (DY6), and 150 plants were planted in each plot. The number of plots per cultivar at the Longchuan and Ruili sites was 7 and the number of plots per cultivar at the Mangshi site was 9, with plot size of 36 m^2. After seedling emergence, five normal, uniformly growing maize plants were chosen from each plot and marked. To determine their yield, data such as aboveground dry, dry seed, and dry mass of the ear organs were measured until the end of their reproductive period.

Physiological development time (PDT) is defined as the time scale relative to optimal developmental conditions (Li et al., 2009), as the following equations:

$$PDT = \sum_{i=1}^{n} PE$$

$$PE = VE \times TSE$$

$$TSE = RTE + SRE - RTE \times SRE$$

$$RTE(T) = \begin{cases} 0 & (T < Tb) \\ (T - Tb)/(Tou - Tb) & (Tb \le T \le Tou) \\ (Tm - T)/(Tm - Tou) & (Tou \le T \le Tm) \\ 0 & (T > Tm) \end{cases}$$

$$SRE = \frac{Tsc \times Q}{30MJ \cdot m^{-2}}$$

where: PE is the daily physiological effect; VE is the early maturity genetic parameter of the cultivar, and DY6 and HD4 were 0.84 and 0.86, respectively; TSE is the temperature and light effect factor; RTE is the relative daily thermal effect; Tb is the lower limit temperature for development; To is the optimal temperature for development; Tm is the upper limit temperature for development; T is the average daily temperature, with values of 10, 24, and 35°C for Tb, To and Tm. SRE is the solar radiation effect; Q is the daily solar radiation; Tsc is the maize temperature sensitivity coefficient, estimated by the parameter debugging, with a value of 0.2.

Taking into account the diurnal temperature difference that affects maize growth and development, it is assumed that the combined effect of daily thermal effects on daily temperature variation comprises 50% of the average temperature (Tav), while 25% of the maximum temperature (Tmax) and 25% of the minimum temperature (Tmin) are each represented as follows:

$$RTE = 0.5 \times RTE(Tav) + 0.25 \times RTE(Tmax) + 0.25 \times RTE(Tmin).$$

The daily dry mass accumulation of maize population was determined by total daily photosynthesis (Mensch formula) and respiratory consumption. The dry mass distribution index is defined as the ratio of dry mass accumulation in each organ to the total dry mass accumulation in the ground at a certain time. On the basis of a generalization and analysis of the existing literature, a dynamic relationship was established between the ear organs distribution index and physiological development time. The fundamental dynamic model is stated as (Xu et al., 2016):

$$DIMEB_{(PDT)} = \frac{DIMEB_m}{\left(1 + \exp\left(-5.036 - 0.1648 \times PDT\right)\right)^{0.2045}} \quad PDT > 41.53$$

$$MEB_{(i)} = DIMEB_{(PDTi)} \times MSB_{(i)}$$

where: $DIMEB_{(PDT)}$ is the distribution index of maize ears biomass at PDT; $DIMEB_m$ is the maximum of distribution index of maize ears biomass, which is a genetic parameter of the model. The values of $DIMEB_m$ are 0.456 and 0.463 for the HD4 and DY6 cultivars, respectively. $MSB_{(i)}$ is the maize shoot biomass at the i^{th} days.

The distribution coefficient is defined as the ratio of daily biomass accumulation of special part to which of total shoot, which remains constant (Yu et al., 2020):

$$DCMEB_i = \frac{\Delta MEB_i}{\Delta MSB_i}$$

$$MEB_i = \sum_{i=0}^{i} (\Delta MSB_i \times DCMEB_i)$$

where $DCMEB_i$ is the distribution coefficient of maize ear biomass at i^{th} days. MEB_i and MSB_i are daily accumulation of maize ears biomass and daily accumulation of maize shoot biomass, respectively.

The final economic yield is determined by the biomass accumulation of the maize ear and the proportion of the economic product (seeds) in the organ (Zhang, 2006):

$$Yield = MEB \times f_e$$

where: yield is the seed yield; and fe is the proportion of seeds to ears organs, estimated by parameter

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debugging given a value of 0.7. MEB is the maize ears biomass at harvest.

The applicability of the model is evaluated by comparing the simulated value with the measured value with a 1:1 graph and various evaluation indices. The most common statistical methods for evaluating the model precision are the root mean square error (RMSE) and the normalized root mean square error (NRMSE), which can reflect the relative error and absolute error between the simulated value and the measured value. The smaller are the RMSE and NRMSE, the better will be the accuracy of the model, as the equations below:

$$\mathrm{RMSE} = \sqrt{\sum_{i=1}^{n} \frac{(Y_i - X_i)^2}{n}}$$

$$\mathrm{NRMSE} = \frac{\mathrm{RMSE}}{\bar{X}_i} \times 100\%$$

where: X_i is the measured value; Y_i is the simulated value; X_i is the average of the measured values; and n is the number of samples.

Results and Discussion

The accumulation and distribution of maize biomass were studied with PDT as the time variable. The RMSE of HD4 and DY6 at the maturity stage was predicted by the PDT model to be 5.12 and 6.47 days, respectively. Due to the different experimental sites, sowing dates, and cultivars, there were certain differences for the aboveground dry mass of maize, which reached the averages of 32,393.98 kg ha^{-1} in Longchuan, 37,813.18 kg ha^{-1} in Ruili, and 28,141.73 kg ha^{-1} in Mangshi. The NRMSE and the RMSE of dry mass models from three stations were 5% and 1,638.78 kg ha^{-1}, respectively. In accordance with the comparison between the simulated and the measured values (Figure 1), both values fell basically near the 1:1 line, and the aboveground dry mass effect of the model was excellent. The NRMSE and the RMSE values of simulated dry mass in the experimental sites were respectively the following ones: in Ruili, 3.11% and 1,177.18 kg ha^{-1}; in Mangshi, 4.15% and 1,169.92 kg ha^{-1}; in Longchuan, 7.1% and 2,302.68 kg ha^{-1}. The comparison of different sites shows that the error of Longchuan is higher than the other two points, but the NRMS were all lower than 10%. The validation results show that the model can accurately simulate the changing trend of maize dry mass in the tropic of southwest China.

There were significant differences for dry mass of ear between the three different sites, and the average dry mass of ear in Ruili was higher than that in Longchuan and Mangshi, with 14,901.23 kg ha^{-1} in Longchuan, 16,846.3 kg ha^{-1} in Ruili, and 12,741.6 kg ha^{-1} in Mangshi. According to the comparison both the simulated and measured values basically fell near the 1:1 line (Figure 2), and the dry mass of ear effect was excellent. The NRMSE and RMSE of the distribution index model for predicting the ear dry mass were 5.44% and 807.22 kg ha^{-1}, respectively. The NRMSE and RMSE of the distribution coefficient model for predicting the ear dry mass were 7.52% and 1,115.3 kg ha^{-1}, respectively. The results show that the NRMSE of both the distribution index and the simulated dry mass of the ear of the distribution coefficient model was within 10%, and that the prediction effect was satisfactory. The comparison of different models shows that the error of the distribution coefficient model is higher than that of the distribution index model. The NRMSE values of the distribution index model of simulated and measured dry mass of the ear in Longchuan, Ruili, and Mangshi were 7.1, 3.51, and 4.76%, respectively, and the RMSE were 1059.23, 596.81 and 606.65 kg ha^{-1}, respectively. The comparison of different sites shows that the error of Longchuan was higher than those of the other two sites.

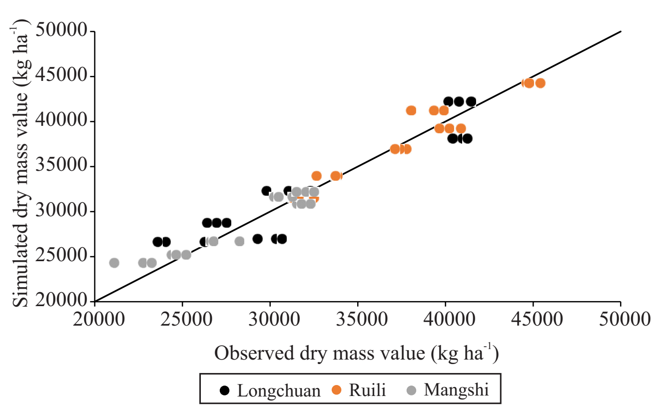

Figure 1. Comparison of simulated and measured aboveground dry mass values of maize (*Zea mays*) in Longchuan, Ruili and Mangshi, Yunnan Province, China.

Due to different environments and sites, yields ranged somewhat between each site, with an average of 9,773.74 kg ha^{-1} in Longchuan, 8,430.39 kg ha^{-1} in Ruili, and 10,786.12 kg ha^{-1} in Mangshi. The comparison of simulated and observed yield are summarized for the two models (Figure 3). The NRMSE and the RMSE of yield predicted by the dry mass distribution coefficient model were 8.6% and 830.76 kg ha^{-1}, respectively. The NRMSE and the RMSE of yield predicted by the dry mass distribution index model were 7.32% and 707.67 kg ha^{-1}, respectively. In the comparison, both simulated and the measured values (Figure 3) fell basically near the 1:1 line, and the yield prediction effect was excellent. The comparison of different models shows that the error of yield predicted by the dry mass distribution coefficient model was higher than the other one. As shown in Figure 4, the NRMSE values of yield predicted by the dry mass distribution index model in Longchuan, Ruili, and Mangshi were 8.96, 5.96, and 7.54%, respectively; and the RMSE were 875.92, 643.69 and 636.3 kg ha^{-1}, respectively. The comparison of different sites shows that the error of Mangshi was higher than that of the other sites. The validation results show that the distribution index model could simulate the changing trend of maize yield more accurately in the tropic of southwest China.

There are more algorithms to simulate yield formation among the currently established models, and their precision varies. During the nutrient growth stage, the dry mass distribution module of the CERES-maize model distributes the photosynthetic products proportionally to roots, stems, and leaves. In the reproductive growth phase, the actual biomass

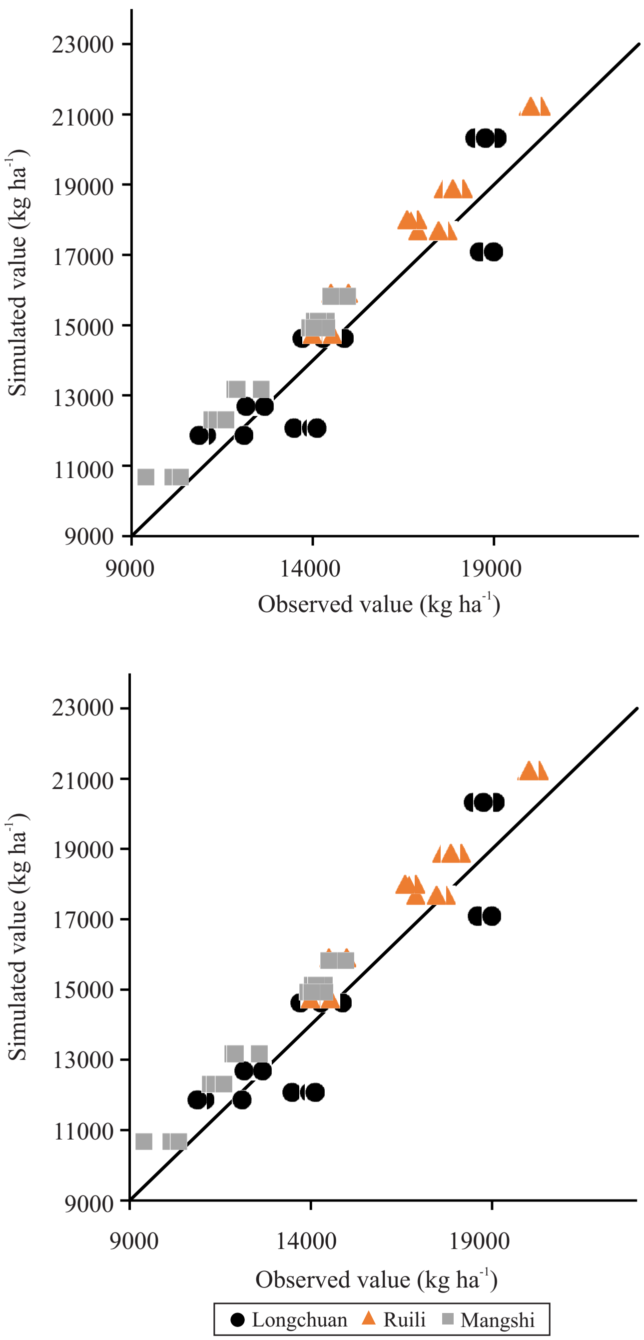

Figure 2. Comparison of simulated and measured values of dry mass of the ear of the winter maize (*Zea mays*) by the distribution coefficient model (left) and the distribution index model (right). Yunnan Province, China.

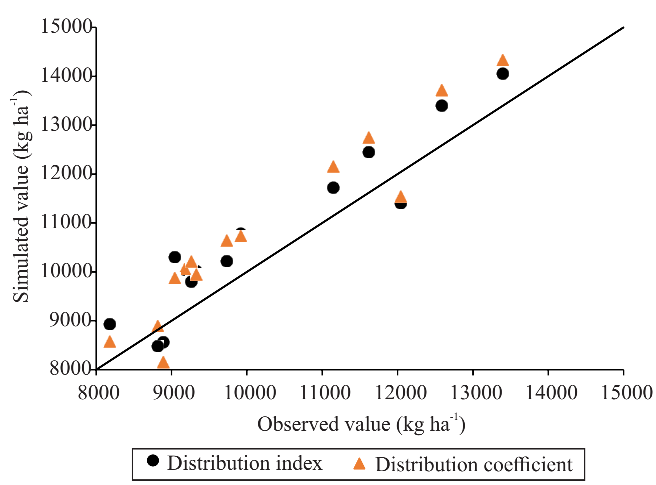

Figure 3. Prediction results of Yunnan winter maize (*Zea mays*) yield verified by distribution index and distribution coefficient models.

increment obtained is calculated to be greater than the potential increment of seeds; and then, biomass increment is allocated to roots and stems (Jones & Kiniry, 1986). The proportion of dry mass allocated to each organ in the APSIM-maize model is dependent on the reproductive stage. At the seedling stage, the root-crown ratio is 1, and at the flowering stage, it is 0.087 (Keating et al., 2003). The dry mass of the WOFOST model is also distributed to the organs in a proportion determined by the developmental period and the reproductive period (Ma & Zhou, 2016). Solar radiation is converted into photosynthetic products by the dry mass allocation module of the EPIC model. Following that, they are distributed to the root system and aboveground parts, with the distribution ratios typically ranging from 0.3 to 0.5, at the root seedling stage, and from 0.05 to 0.2, at the maturity stage (Li et al., 2004). These models are predicted on a single hypothesis for dry mass allocation, which defines the allocation ratio as a fixed value that influences the precision of dry mass allocation and the formation of yield dynamics.

The methods of distribution index and distribution coefficient in the present study are commonly used in empirical models. Some authors accurately simulated winter wheat, castor, tulip, and tomato crops using two simulation models (Shi et al., 2016; Xu et al., 2016; Chen et al., 2019; Li et al., 2019). The results of previous studies on the dry mass distribution index model and the coefficient model provide reliability for the current study. The results of the present work are consistent with previous studies on other crops, which verified its scientific validity (Lü et al., 2013). The model can accurately simulate the growth and yield changes of winter maize in southwest China. In addition, the dry mass allocation index model shows a high prediction accuracy regarding the adaptability of ear dry mass and yield of maize. Therefore, it is capable of enhancing the overall accuracy of the model. The application of the dry mass distribution index model can also assist in the future improvement of winter maize yield in the region, and it is essential for the analysis of winter maize crop production.

Moreover, the uncertainty of various parameters and input drivers constituted an important reason for the inaccurate simulation results. Furthermore, the model does not take into account such factors as water and fertilizer, which leads to errors in model prediction and needs further study.

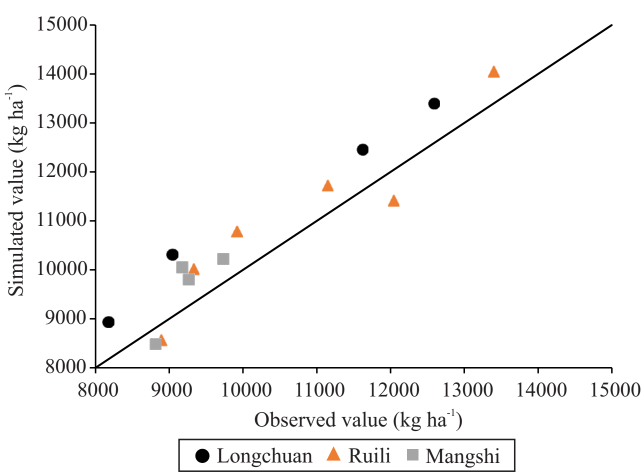

Figure 4. Prediction results of winter maize (*Zea mays*) yield verified by distribution index model, in three stations, in Yunnan.

Conclusions

1. The model for dry mass distribution and yield prediction in maize (*Zea mays*) based on physiological development time is established.

2. Normalized root mean square error of aboveground dry mass, ear dry mass, and yield are generally less than 10% in different sites, which could effectively simulate winter maize in Yunnan tropical region.

3. A comparative study between the dry mass distribution index model and the distribution coefficient model shows that the accuracy of the dry mass distribution index model is higher than that of the distribution coefficient model.

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References

AMIRI, E.; IRMAK, S.; YAGHOUTI, H. Performance of WOFOST model for simulating maize growth, leaf area index, biomass, grain yield, yield gap, and soil water under irrigation and rainfed conditions. **Journal of Irrigation and Drainage Engineering**, v.148, art.05021005, 2022. DOI: https://doi.org/10.1061/(ASCE)IR.1943-4774.0001644.

CAI, F.; MI, N.; MING, H.; ZHANG, S.; ZHANG, H.; ZHAO, X.; ZHANG, Y.; ZHANG, B. Effects of improving evapotranspiration parameterization scheme on WOFOST model performance in simulating maize drought stress process. **Journal of Applied Meteorological Science**, v.32, p.52-64, 2021.

CHEN, C.; WEI-DONG, Y.; JIN-TAO, Y.; HAI-PENG, L.; LI-PING, F. Simulation model of material accumulation and distribution of fresh cut tulips of different varieties. **Chinese Journal of Agrometeorology**, v.40, p.758-771, 2019. DOI: https://doi.org/10.3969/j.issn.1000-6362.2019.12.003.

COHEN, D. Maximizing final yield when growth is limited by time or by limiting resources. **Journal of Theoretical Biology**, v.33, p.299-307, 1971. DOI: https://doi.org/10.1016/0022-5193(71)90068-3.

CONTRERAS, J.I.; BUENO, I.; LAO, M.T.; SEGURA, M.L. Green bean under organic and integrated crop systems in a Mediterranean area greenhouse: effects on dry matter and nutrient-extraction distribution pattern. **Communications in Soil Science and Plant Analysis**, v.44, p.776-782, 2013. DOI: https://doi.org/10.1080/00103624.2013.748860.

DI BENE, C.; DIACONO, M.; MONTEMURRO, F.; TESTANI, E.; FARINA, R. EPIC model simulation to assess effective agro-ecological practices for climate change mitigation and adaptation in organic vegetable system. **Agronomy for Sustainable Development**, v.42, art.7, 2022. DOI: https://doi.org/10.1007/s13593-021-00745-5.

ELMORE, R.W.; SAWYER, J.E.; BOYER, M.J.; WOLI, K.P. Updating an old paradigm corn growth, development, dry matter, and nutrient accumulation and partitioning. **Crops & Soils**, v.52, p.34-58, 2019. DOI: https://doi.org/10.2134/cs2019.52.0213.

FRIEDLINGSTEIN, P.; JOEL, G.; FIELD, C.B.; FUNG, I.Y. Toward an allocation scheme for global terrestrial carbon models. **Global Change Biology**, p.755-770, 1999. DOI: https://doi.org/10.1046/j.1365-2486.1999.00269.x.

IUSS WORKING GROUP WRB. **World Reference Base for Soil Resources 2014**: international soil classification system for naming soils and creating legends for soil maps: update 2015. Rome: FAO, 2015. (FAO. World Soil Resources Reports, 106).

JONES, C.A.; KINIRY, J.R. (Ed.). **CERES-Maize**: a simulation model of maize growth and development. San Marcos: Texas A&M University Press, 1986.

KEATING, B.A.; CARBERRY, P.S.; HAMMER, G.L.; PROBERT, M.E.; ROBERTSON, M.J.; HOLZWORTH, D.; HUTH, N.I.; HARGREAVES, J.N.G.; MEINKE, H.; HOCHMAN, Z.; MCLEAN, G.; VERBURG, K.; SNOW, V.; DIMES, J.P.; SILBURN, M.; WANG, E.; BROWN, S.; BRISTOW, K.L.; ASSENG, S.; CHAPMAN, S.; MCCOWN, R.L.; FREEBAIRN, D.M.; SMITH, C.J. An overview of APSIM, a model designed for farming systems simulation. **European Journal of Agronomy**, v.18, p.267-288, 2003. DOI: https://doi.org/10.1016/S1161-0301(02)00108-9.

LEVIS, S.; BADGER, A.; DREWNIAK, B.; NEVISON, C.; REN, X. CLMcrop yields and water requirements: avoided impacts by choosing RCP 4.5 over 8.5. **Climatic Change**, v.146, p.501-515, 2018. DOI: https://doi.org/10.1007/s10584-016-1654-9.

LI, H.; TAN, F.Y.; WANG, J.L.; TAN, K.Y.; XU, Y.; WANG, Z.W. Simulation on dry matter distribution coefficient for summer maize in North China. **Chinese Journal of Agrometeorology**, v.37, p.335-342, 2016. DOI: https://doi.org/10.3969/j.issn.1000-6362.2016.03.009.

LI, J.; SHAO, M.; ZHANG, X.; WILLIAMS, J.R. Simulation equations for crop growth and yield formation in the EPIC model. **Journal of Northwest A&F University (Natural Science Edition)**, v.32(B1), p.25-30, 2004. DOI: https://doi.org/10.13207/j.cnki.jnwafu.2004.s1.007.

LI, S.; ZHU, Y.; ZHANG, H.; LIU, S.; LIU, H.; DU, M. Simulating winter wheat geometrical parameters of each organ using the whole plant dry matter weight distribution index model. **Transactions of the Chinese Society of Agricultural Engineering**, v.35, p.155-164, 2019. DOI: https://doi.org/10.11975/j.issn.1002-6819.2019.09.019.

LI, W.; MENG, Y.-L.; ZHAO, X.-H.; CHEN, B.-L.; XU, N.-Y.; ZHOU, Z.-G. Modeling of cotton boll maturation period and cottonseed biomass accumulation. **Chinese Journal of Applied Ecology**, v.20, p.879-886, 2009.

LÜ, S.; YANG, X.; ZHAO, J.; LIU, Z.; LI, K.; MU, C.; CHEN, X.; CHEN, F.; MI, G. Effects of climate change and variety alternative on potential yield of spring maize in Northeast China. **Transactions of the Chinese Society of Agricultural Engineering**, v.29, p.179-190, 2013.

MA, X.; ZHOU, G. Maize biomass simulation based on dynamic photosynthate allocation. **Chinese Journal of Applied Ecology**, v.27, p.2292-2300, 2016. DOI: https://doi.org/10.13287/j.1001-9332.201607.026.

PING, X.-Y.; ZHOU, G.-S.; SUN, J.-S. Advances in the study of photosynthate allocation and its controls. **Chinese Journal of Plant Ecology**, v.34, p.100-111, 2010.

RUGIRA, P.; MA, J.; ZHENG, L.; WU, C.; LIU, E. Application of DSSAT CERES-maize to identify the optimum irrigation management and sowing dates on improving maize yield in northern China. **Agronomy**, v.11, art.674, 2021. DOI: https://doi.org/10.3390/agronomy11040674.

SHI, X.; CAI, H.; ZHAO, L.; YANG, P.; WANG, Z. Greenhouse tomato dry matter production and distribution model under condition of irrigation based on product of thermal effectiveness and photosynthesis active radiation. **Transactions of the Chinese Society of Agricultural Engineering**, v.32, p.69-77, 2016. DOI: https://doi.org/10.11975/j.issn.1002-6819.2016.03.011.

TAN, F.-Y.; LI, H.; WANG, J.-L.; WANG, Z.-W. Response of dry matter partitioning coefficient of summer maize to drought stress in North China. **Chinese Journal of Applied Ecology**, v.30, p.217-223, 2019. DOI: https://doi.org/10.13287/j.1001-9332.201901.031.

WANG, J.; DONG, X.; QIU, R.; LOU, B.; TIAN, L.; CHEN, P.; ZHANG, X.; LIU, X.; SUN, H. Optimization of sowing date and irrigation schedule of maize in different cropping systems by APSIM for realizing grain mechanical harvesting in the North China Plain. **Agricultural Water Management**, v.276, art.108068, 2023. DOI: https://doi.org/10.1016/j.agwat.2022.108068.

XU, S.-J.; WANG, Y.; ZHU, G.-L. Model for predicting dry matter distribution in castor. **Chinese Journal of Oil Crop Sciences**, v.38, p.344-349, 2016.

YU, T.-G.; RAN, H.; DENG, X.; HU, X.-T. Dynamic response and simulation of dry matter and nitrogen distribution of hybrid seed maize to water and nitrogen stress in northwest arid region of China. **Water Saving Irrigation**, n.6, p.73- 80+86, 2020.

ZENG, Z. Analysis of the current situation of maize production in China and suggestions. **Grain Oil and Feed Technology**, v.187, p.4-8, 2022. Available at: <https://jxsl.cbpt.cnki.net/WKD/WebPublication/paperDigest.aspx?paperID=4fe7ae78-4f12-4137-bdda-8096237294aa>. Accessed on: Sept. 29 2023.

ZHANG, X. **Study on summer maize growth simulation model of Loess areas**. Yangling: Northwest A&F University, 2007. Available at: <https://max.book118.com/html/2018/0224/154536346.shtm>. Accessed on: Sept. 29 2023.