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MODEL AND ANALYZE PLANT GROWTH AFFECTED BY WATER DEFICITS

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Abstract. *Water deficit stress known as drought stress was common encountered to plant. It limited growth and distribution of plants more than any other environmental factors did. A method was proposed to simulate growth of plant affected by water deficits. An index called water deficit degree which integrated water deficit intensity, duration and plant resistance together was introduced to assess level of water deficit of the whole plant. By constructing power functions to characterize plant physiological processes affected by water deficit degree, growth of plant under water deficits was simulated. Dataset of maize under contrasted water regimes was used to validate the proposed method. Results show that the proposed model can predict the impact of water deficits on development of plant.*

Keywords: Plant modeling and simulation, Water deficit index, Source-sink model, Functional and structural plant model

1. Introduction.

Water is vital for plant growth and development. Water deficit stress known as drought stress is commonly encountered. Permanently or temporarily, it limits growth and distribution of natural vegetation and performance of cultivated plants more than any other environmental factors do [1]. Water stresses adversely influence on physiological processes such as organ growth, photosynthesis and morphological parameters of plants [2]. So models are powerful tools for analyzing the importance of water availability within the plant growth. For example, models had been represented to develop tree architecture for apple [3] and peach [4] including water stress effects. And some water deficit indexes were also proposed to estimate level of water deficit. In agricultural production systems simulator (APSIM), the water deficit factor was calculated as the ratio or fraction available water in the root zone [5]. However, in CropSyst model, the water deficit factor was defined as actual to potential transpiration ration [6].

According to Chaves et al. [7], the reactions of the plant to water deficit stress differed significantly depending upon the intensity, duration of water deficit and plant resistance to water deficit, but the above models or indexes only took water deficit intensity into account to influence plant development. So this paper presented a method to simulate plant growth under water deficit stress and to integrate the knowledge of plant physiology and morphology. The main content was to introduce an index called water deficit degree to quantify water deficit stress integrating the intensity, duration of water deficit as well as the plant resistance together. Then the index was incorporated with source-sink model to model plant growth under water deficit conditions. Maize dataset of Song et al. [15] under contrasted water regimes was used to analyze and validate the proposed model. The results showed that water deficit degree had less fluctuating characteristic to reflect water deficit and the proposed model could simulate reasonably well for virtual plant under water deficits during the vegetative stage.

2. Model Description.

2.1. Water deficit degree.

In the presented model, water deficit index called water deficit degree was introduced like Mailhol et al. [8]:

$$WDD_j = \left(\sum_{j-D}^{j} ET \Bigg/ \sum_{j-D}^{j} ET_{pot} \right)^{\gamma} \tag{1}$$

where WDD_j was the water deficit degree on day j; ET was actual plant transpiration and ET_{pot} was maximal plant transpiration; γ was an empirical parameter which depends on the sensitivity of the plant to water deficit; D was the day interval. It could be observed that result of Equation (1) would access water status of the whole plant during D days and also be used as a global index to plant growth.

Maximal transpiration (ET_{pot}) was defined as the transpiration of water from plant leaves to the atmosphere when the soil moisture content was unrestricted. ET_{pot} was determined by the leaf area and potential transpiration rate per unit leaf area (T_o) and total area of leaves. The biomass per unit area for blade (SLA) was assumed to be constant during the period of simulation, so ET_{pot} could be calculated as:

$$ET_{pot} = T_o * W_L/SLA \tag{2}$$

where T_o was calculated by the S-W model [9], W_L was the sum biomass of all green leaves. Here, we assumed that actual transpiration was determined by total water uptake by root. Under no-stress conditions, the actual transpiration equaled the maximal transpiration; on the contrary, the actual transpiration equaled water uptake. We adopted the classical root water-uptake model [10] to calculate water uptake (WU):

$$WU = \theta * E_r * W_R/SRL * \psi_{\max} \tag{3}$$

where θ was the ratio volumetric water contents and filed moisture capacity of soil; E_r was root membrane permeability per unit length; SRL was biomass of root per unit length; $\psi_{\max}$ was max difference between average soil water potential at a depth of 120 cm and water potential of plant root; W_R was total biomass of root. We considered root as whole. So actual transpiration could be defined as:

$$ET = \begin{cases} WU, & WU \geq ET_{pot} \\ ET_{pot}, & \text{else} \end{cases} \tag{4}$$

2.2. Source-sink model.

One of the simplest photosynthesis approaches was often used in crop growth models to compute the photosynthetic rate (P) which was defined as the product of the maximum photosynthetic rate ($P_{\max}$) in optimal environmental conditions, initial photochemical efficiency (a), photosynthetically active radiation (PAR) absorbed by the leaf, the accelerating effect of temperature (T), as well as water deficit degree [11].

$$P = P_{\max} a * PAR/(P_{\max} + a * PAR) * g_1(WDD) * g_2(T) \tag{5}$$

where the function $g_1(WDD)$ was effect of water deficit degree to photosynthesis. It would be constructed as the power function:

$$g_1(WDD) = WDD^{\beta_P} \tag{6}$$

β_P was a constant parameter indicating sensitivity of photosynthesis to WDD. Subsequently, at a certain simulation step t, biomass available for growth ($Q(t)$) could be calculated using the method reviewed by Franklin et al. [12]. Relative sink strength principle was used to estimate the amount of biomass ($G_j(t)$) which was allocated to a sink organ j at a certain simulation step t [13]:

$$G_j(t) = \min \left(\frac{AD_j(t)}{\sum_{i=1}^{n} AD_j(t)} * Q(t), D_j(t) \right) \tag{7}$$

$AD_j(t)$ was the actual biomass demand for growth at a certain simulation step t; $D_j(t)$ was the potential biomass demand for growth at a certain simulation step t which could be affected by WDD:

$$AD_j(t) = D_j(t) * WDD^{\beta_O} \tag{8}$$

where β_O was a constant parameter indicating sensitivity of organ to WDD; O was the organ type which could be B (blade), I (internode), S (sheath) and R (root). Then size of an organ at certain simulation step affected by WDD could be calculated using Qu's method [14].

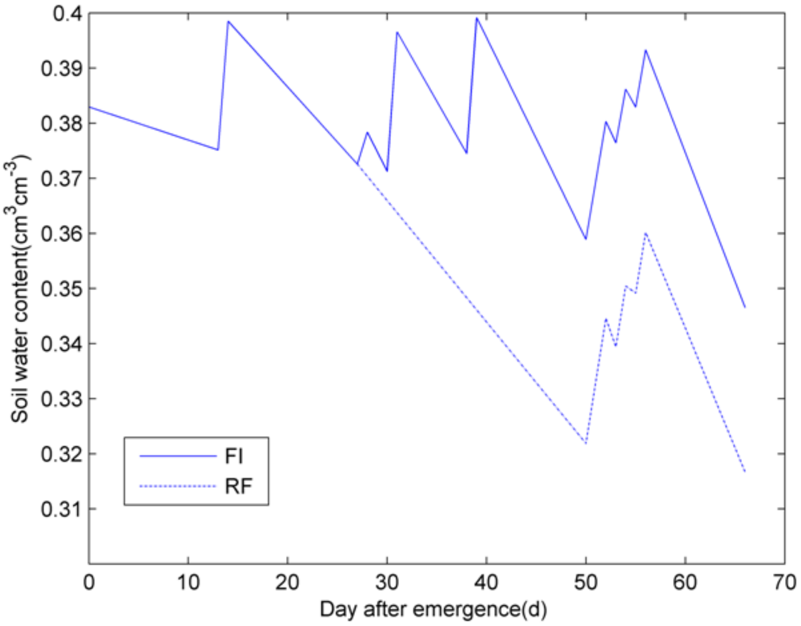

Figure 1. Soil volumetric water content under two water regimes

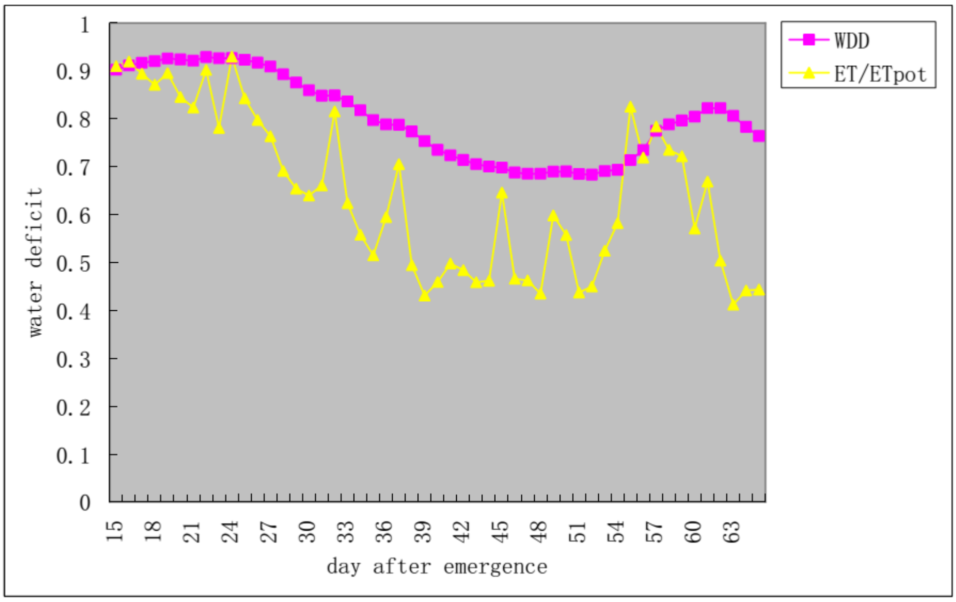

Figure 2. Comparisons of water deficit between WDD and ET/ET_{pot}

3. **Main Results.** In order to validate the proposed model, maize data (Pioneer 34N43) of Song et al. [15] under contrasted water regimes would be used. The field experiments were conducted in 2006-07 at the University of Queensland, Gatton Campus, Australia (latitude 27°33′S, longitude 152°20′E). Chemically treated seeds were sown on September 6, 2006 and emerged 10 days after sowing. There were two water regimes by combining rainfall and irrigation (Figure 1): (a) FI, fully irrigated throughout growth as the control treatment, (b) RF, rained treatment in which crops were not irrigated for the whole season. In the present model, we used maize data under FI water regime as input data to estimate maize data under RF regime to test the proposed model. We got environment data from Australian Government Bureau of Meteorology (http://www.bom.gov.au/climate/data/).

Figure 2 showed the comparisons of water deficit indexes between WDD and ET/ET_{pot} which did not integrate time and plant resistance. In the presented model, we set the day interval $D = 10$. It could be observed that trend of WDD was more consistent with the change of soil volumetric water content under RF condition. The curve of WDD fluctuated less dramatically than that of ET/ET_{pot}. So when soil volumetric water content changes, the WDD could capture water deficit well.

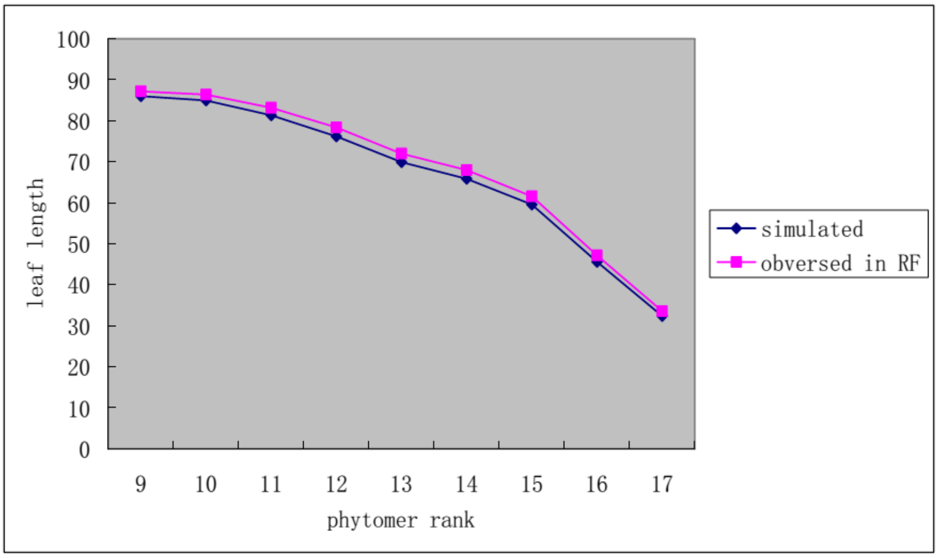

FIGURE 3. Final lengths of individual leaf in simulated and RF water regimes

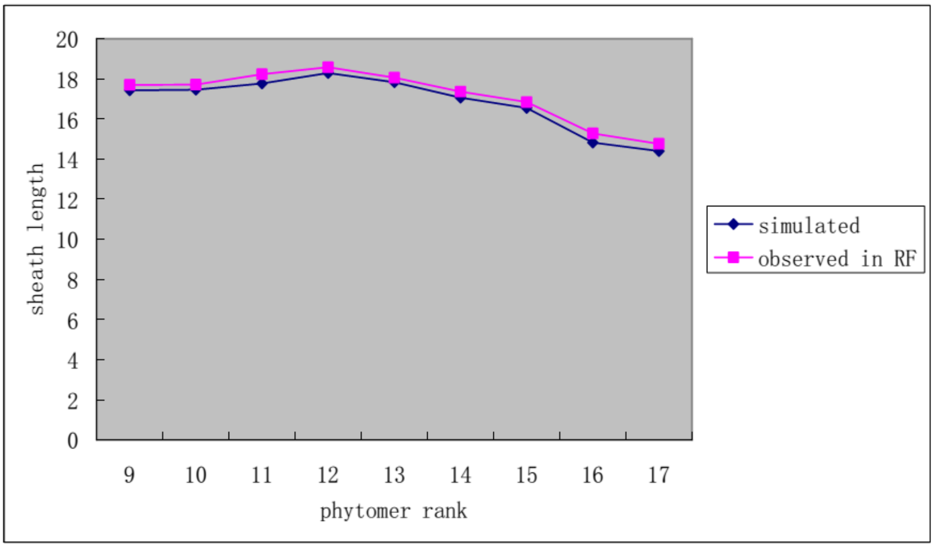

FIGURE 4. Final lengths of individual sheath in simulated and RF water regimes

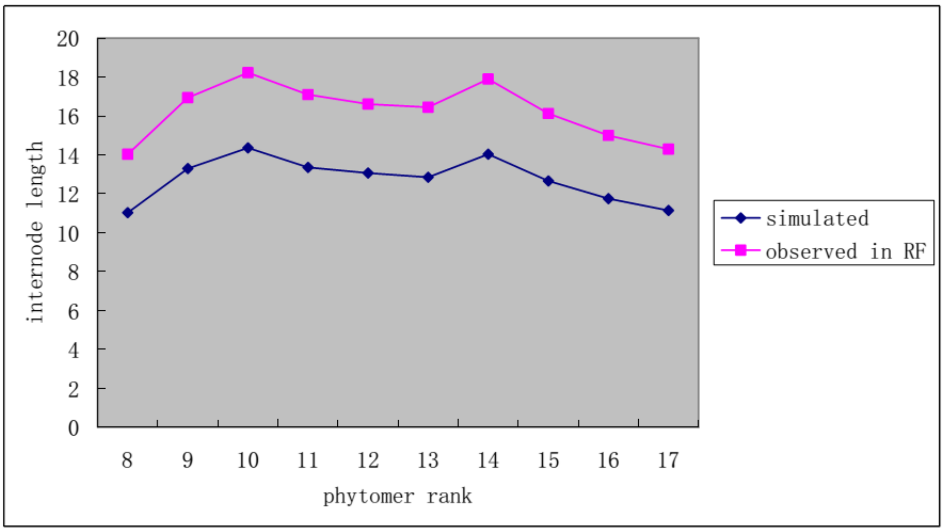

Figure 5. Final lengths of individual internode in simulated and RF water regimes

In this part, we integrated *WDD* to simulate plant growth. Model estimated values were compared with the observed values using standard statistics and regression analysis. Mean absolute error (MAE) and root mean squared error (RMSE) were computed as criteria to quantify and understand the difference between results of simulation and field. Figures 3, 4, 5 presented comparisons of simulated and observed final lengths of leaf, sheath and internode under RF water regime (Figure 3: RMSE = 1.7784, MAE = 1.7364; Figure 4: RMSE = 0.3340, MAE = 0.3245; Figure 5: RMSE = 3.5223, MAE = 3.5110). The results showed that the proposed model could simulate reasonably well for virtual maize under water deficits during the vegetative stage of maize development.

4. **Conclusions.**

The presented works proposed an approach to simulate plant development integrating knowledge of plant under water deficit stress. The allocation of biomass to different plant parts was determined by product of *WDD*, growth and photosynthesis. Growth of organ, in turn, would affect water loose and uptake from shoot and root parts. This was a feedback control loop.

Firstly, we defined a water deficit degree including factors of intensity, duration and resistance. Then we used it to affect plant functions such as photosynthesis and growth of organ. Development of plant was achieved by productions of L-system. A set of experiments demonstrated that our method could reproduce main features of plant anatomical changes (length, area) under water deficit conditions. By comparing results from simulation and field, it can be concluded that the water deficit degree can reflect water deficit better than the index (ET/ET_{pot}) and the proposed model can also simulate reasonably well for virtual plant under water deficits.

Several issues remained open for further research. In present model, we use a plant species dependent constant, indicating plant resistance to water deficit. However, in reality, plant resistance to water deficit stress is related with plant development stages. Another issue is that rate to produce new leaf also is affected by water deficit, so influences of water deficit stress to branching initiation and senescence should also be considered. New model of root structure and development such as 2D or 3D water uptake model should be considered in order to improve accuracy of *WDD*.

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REFERENCES

[1] N. J. Atkinson and P. E. Urwin, The interaction of plant biotic and abiotic stresses: From genes to the field, *Journal of Experimental Botany*, vol.63, no.10, pp.3523-3543, 2012.

[2] P. U. Rani and K. Prasannalaxmi, Water stress induced physiological and biochemical changes in Piper betle L. and Ricinus communis L. plants and their effects on Spodoptera litura, *Allelopathy Journal*, vol.33, no.1, pp.25-41, 2014.

[3] M. Génard, J. Dauzat, N. Franck et al., Carbon allocation in fruit trees: From theory to modelling, *Trees*, vol.22, no.3, pp.269-282, 2008.

[4] G. Lopez, M. Behboudian, X. Vallverdu et al., Mitigation of severe water stress by fruit thinning in 'O'Henry' peach: Implications for fruit quality, *Scientia Horticulturae*, vol.125, no.3, pp.294-300, 2010.

[5] B. A. Keating, P. S. Carberry, G. L. Hammer et al., An overview of APSIM, a model designed for farming systems simulation, *European Journal of Agronomy*, vol.18, no.3, pp.267-288, 2003.

[6] C. O. Stöckle, M. Donatelli and R. Nelson, CropSyst, a cropping systems simulation model, *European Journal of Agronomy*, vol.18, no.3, pp.289-307, 2003.

[7] M. M. Chaves, J. P. Maroco and J. S. Pereira, Understanding plant responses to drought – From genes to the whole plant, *Functional Plant Biology*, vol.30, no.3, pp.239-264, 2003.

[8] J. C. Mailhol, A. A. Olufayo and P. Ruelle, Sorghum and sunflower evapotranspiration and yield from simulated leaf area index, *Agricultural Water Management*, vol.35, no.1, pp.167-182, 1997.

[9] W. J. Shuttleworth and J. Wallace, Evaporation from sparse crops – An energy combination theory, *Quarterly Journal of the Royal Meteorological Society*, vol.111, no.469, pp.839-855, 1985.

[10] W. Herkelrath, E. Miller and W. Gardner, Water uptake by plants: II. The root contact model, *Soil Science Society of America Journal*, vol.41, no.6, pp.1039-1043, 1977.

[11] X. L. Roux, A. Lacointe, A. Escobar-Gutiérrez et al., Carbon-based models of individual tree growth: A critical appraisal, *Annals of Forest Science*, vol.58, no.5, pp.469-506, 2001.

[12] O. Franklin, J. Johansson, R. C. Dewar et al., Modeling carbon allocation in trees: A search for principles, *Tree Physiology*, 2012.

[13] E. Heuvelink, Dry matter partitioning in tomato: Validation of a dynamic simulation model, *Annals of Botany*, vol.77, no.1, pp.71-80, 1996.

[14] H. Qu, Q. Zhu, M. Guo et al., Simulation of carbon-based model for virtual plants as complex adaptive system, *Simulation Modelling Practice and Theory*, vol.18, no.6, pp.677-695, 2010.

[15] Y. Song, C. Birch and J. Hanan, Maize canopy production under contrasted water regimes, *Annals of Applied Biology*, vol.157, no.1, pp.111-123, 2010.