Postprint: Effects of Root Water Stress Response Functions on Soil Water, Crop Growth Dynamics, and Yield Simulation

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Abstract

To investigate the influence of root water stress response functions on field water dynamics and yield simulation, soil water dynamics and wheat yield were simulated using the Richards equation and the PS123 crop growth model, with comparative analysis conducted among three water stress response functions: VG (S-shaped curve), MP (concave-convex curve), and LS (S-shaped curve). Experimental data from Huoquan Station (3 years) and Xiaohe Station (2 years) in Shanxi Province were employed to invert the soil hydraulic characteristic parameters and water stress response function parameters in the model, thereby determining optimal parameter values and obtaining simulation results for soil water content, evapotranspiration, and grain yield. The results indicated that: (1) Under VG, MP, and LS function conditions, the simulation results for soil water content and yield were all satisfactory, with Root Mean Square Error (RMSE) values ranging between 0.021 and 0.036, and the test between simulated and measured values achieved extremely significant levels; for Huoquan Station, the average relative errors between simulated and measured soil water content under VG, MP, and LS function conditions were 6.37%, 8.26%, and 7.18%, respectively, with the minimum correlation coefficient value being 0.7814, and the average relative errors of simulated yield were 8.73%, 8.40%, and 8.42%, respectively; for Xiaohe Station, the average relative errors between simulated and measured soil water content were generally larger than those at Huoquan Station, with a maximum value of 12.47%. (2) In soil water dynamics simulation, S-shaped curve water stress response functions exhibited superior performance compared to concave-convex curve water stress response functions, wherein simulations using the VG function yielded smaller average relative errors and evapotranspiration values closer to measured values. (3) In yield simulation, differences among the three water stress response functions were not significant. In conclusion, the VG function represents a root water stress response function with relatively high accuracy, and the model is concise

and convenient; the improved LS function can enhance simulation accuracy, but the stability of the model requires further investigation.

Full Text

Effect of Root Water Stress Response Function on Soil Water, Crop Growth Dynamics, and Yield Simulation

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Abstract

To investigate the influence of root water stress response functions on farmland water dynamics and yield simulation, this study simulated soil water dynamics and wheat yield using the Richards equation and PS123 crop growth model. Three moisture stress response functions were compared and analyzed: the Van Genuchten function (S-shaped curve), a power function (convex curve), and a modified piecewise function (S-shaped curve). Measured data from Huoquan Station (three years) and Xiaohe Station (two years) in Shanxi Province were used to invert soil hydraulic characteristic parameters and moisture stress response function parameters, determining optimal values. The results show: (1) All three functions produced satisfactory simulations of soil moisture and yield, with regression standard error (RMSE) values between 0.021 and 0.036, and correlation coefficients reaching highly significant levels. For Huoquan Station, the average relative errors between simulated and measured soil moisture content were 6.37%, 8.26%, and 7.18% for the three functions, respectively, while the average relative errors for grain yield were 8.73%, 8.40%, and 8.42%. For Xiaohe Station, soil moisture simulation errors were generally larger than at Huoquan Station, with a maximum of 12.47%. (2) For soil water dynamics simulation, S-shaped curve functions performed better than convex-type functions, with the Van Genuchten function showing smaller average relative errors and evapotranspiration values closer to measurements. (3) For yield simulation, no significant differences were observed among the three functions. In conclusion, the Van Genuchten function is a high-precision, concise, and convenient root water stress response function, while the improved piecewise function can enhance simulation accuracy but requires further investigation of its stability.

Keywords: water stress; root water uptake model; farmland water simulation; yield simulation; parameter inversion

1. Introduction

Root water stress response functions, defined as the ratio of actual to maximum root water uptake rates, are critical parameters for studying drought stress effects on root water absorption. Root water uptake forms the basis for plant water and nutrient acquisition and photosynthesis, linking the water and carbon cycles. In simulations of soil water dynamics and crop yield, root water uptake models are essential components whose accuracy directly affects simulation quality.

Empirical models under macroscopic conditions are commonly used to simulate root water uptake processes, primarily considering relationships among root density distribution, soil moisture profile, and transpiration rate. Since direct measurement of crop root water uptake rates is difficult, researchers have developed improved models for arid regions by introducing soil moisture-related parameters. These moisture stress response functions, expressed as piecewise functions of soil water content or matric potential, include both linear and nonlinear forms. Linear functions indicate that root water uptake rate decreases linearly with soil matric potential or water content, with the Feddes model being the most representative. Nonlinear functions include S-shaped and convex types, both suggesting a gradual process of root water uptake rate change with soil matric potential or water content, represented by the Van Genuchten function and Kang Shaozhong' s exponential model for wheat, respectively.

Compared with linear functions, nonlinear soil moisture stress response functions can more accurately characterize soil moisture effects on root water uptake in most cases. However, S-shaped response functions exhibit abrupt rate changes at segment connection points, inconsistent with the continuous, gradual nature of crop growth. To address this limitation, this study proposes an improved S-shaped moisture stress response function using soil water content as the variable, comparing it with two other typical functions through crop-water simulation processes.

Crop growth models are essential tools for quantitatively evaluating field management practices such as irrigation and fertilization, simulating soil water, nitrogen, and crop growth. While models like WOFOST use simplified water balance methods, others such as DSSAT, PS123, and HYDRUS-1D employ Richards equation-based soil water dynamics models that are more suitable for complex boundary conditions with higher accuracy. The PS123 model, developed by the Dutch research group led by Professor De Wit, emphasizes crop commonality and integrates closely with physiological and ecological mechanisms, showing good applicability in China.

2. Materials and Methods

2.1 Study Area Description

This study focused on winter wheat using experimental data from two stations in Shanxi Province: Huoquan and Xiaohe.

Huoquan Station is located in Dong' an Village, Guangsheng Temple Town, Hongdong County (36°17 35 N, 111°46 21 E), at 529 m elevation. The region has a warm temperate continental climate with light loam soil (bulk density 1.46 g · cm ^{3}, field capacity 0.4044 cm^{3} · cm ^{3}).

Xiaohe Station is located in Yangcun, Yuci District, Jinzhong City (37°39 06 N, 112°41 31 E), at 782.64 m elevation. The region has similar climate with heavy loam soil (bulk density 1.42 g · cm ^{3}, field capacity 0.3592 cm^{3} · cm ^{3}).

The study utilized three years of winter wheat data from Huoquan Station (2016-2019) and two years from Xiaohe Station (2017-2019), including meteorological data, dry matter measurements, and soil moisture data. Soil moisture was measured by oven-drying at Huoquan Station and neutron probe at Xiaohe Station. Huoquan conducted field experiments (plot area 66.7 m^{2}), while Xiaohe used bottomless lysimeters (3.33 m $\times$ 2 m).

2.2 Experimental Design

Both stations conducted winter wheat water-fertilizer coupling experiments. Huoquan Station established 9 treatments annually, while Xiaohe Station had 8 treatments. For model parameter calibration, this study selected high-water, medium-water, and zero-water treatments each year. Detailed treatment information is shown in Table 1, noting that fertilization quantities varied across years and treatments, making the observed changes in soil moisture, evapotranspiration, and yield results of combined water-fertilizer effects.

2.3 Model Formulation

2.3.1 Soil Water-Heat Coupled Dynamic Simulation Model The study considered temperature variations during the winter wheat growth period, using the Richards equation with a root water uptake term for soil moisture dynamics simulation. The simulation period covered the entire growth stage, with layered simulation of moisture content and heat flow from the surface to 100 cm depth. The theoretical model analyzed soil temperature effects on soil water movement parameters. The water-heat coupling equation from Shang Songhao et al. was adopted, which comprehensively considers soil water migration, heat conduction, and water phase change. Compared with traditional coupling equations, this formulation significantly reduces coupling complexity by ignoring phase change effects and only correcting ice and unfrozen water content at the end of each calculation period according to the freezing curve, thereby improving iterative solution efficiency.

The governing equation is:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[D(\theta)\frac{\partial \theta}{\partial z}\right] - \frac{\partial K(\theta)}{\partial z} + S(z,t)$$

where θ is soil volumetric water content (cm^3 · cm ^{3}), t is time (min), z is depth (cm), $D(\theta)$ is soil unsaturated diffusivity (cm^2 · min ^{1}), $K(\theta)$ is soil unsaturated hydraulic conductivity (cm · min ^{1}), and $S(z,t)$ is root water uptake rate (cm^3 · cm ^{3} · min ^{1}).

The soil water characteristic curve is described by:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1+(\alpha h)^n]^m}$$

where θ_s is saturated water content, θ_r is residual water content, h is soil matric potential (cm), and α, n, m are shape parameters.

The complete water-heat coupling model consists of the above equations with initial and boundary conditions. Initial soil moisture content was measured on the sowing date, air temperature from automatic weather stations, and ground temperature from thermometers. The upper boundary condition set surface flux equal to soil evaporation, with ground temperature calculated from empirical relationships between air and surface temperatures. Lower boundary conditions used Type I boundaries due to minimal variations in temperature and soil moisture during the wheat growth period. The model was solved using finite difference methods to obtain temporal variations of layered soil moisture and temperature.

2.3.2 Root Water Uptake Model Actual root water uptake rate was calculated as the product of potential uptake rate and moisture stress response function:

$$S(z,t) = \beta(\theta) \cdot S_p(z,t)$$

where $S(z,t)$ is actual root water uptake rate (cm^3 · cm ^{3} · min ^{1}), $S_p(z,t)$ is potential root water uptake rate under sufficient water conditions (cm^3 · cm ^{3} · min ^{1}), and $\beta(\theta)$ is the moisture stress response function.

Three forms of moisture stress response functions were compared:

1. **Van Genuchten function (VG)**: An S-shaped curve using soil matric potential as variable:

   $$\beta(h) = \frac{1}{1+(h/h_{50})^P}$$

   where h_{50} is the soil water potential when transpiration reduces to 50% of maximum, and P is an empirical coefficient.

2. **Power function (MP)**: A convex curve using soil water content as variable:

$$\beta(\theta) = \left(\frac{\theta - \theta_{wp}}{\theta_j - \theta_{wp}}\right)^A$$

where θ_j is critical soil water content, θ_{wp} is wilting point water content, and A is an empirical coefficient.

3. **Modified piecewise function (LS)**: An improved S-shaped curve eliminating rate 突变 at connection points:

$$\beta(\theta) = \begin{cases} 1 & \theta \geq \theta_j \\ \left(\frac{\theta - \theta_{wp}}{\theta_j - \theta_{wp}}\right)^{B(\theta - \theta_{wp}) + C} & \theta_{wp} < \theta < \theta_j \\ 0 & \theta \leq \theta_{wp} \end{cases}$$

where B and C are empirical coefficients.

2.3.3 Winter Wheat Yield Simulation The PS123 crop growth model simulated winter wheat yield, considering effective solar radiation, temperature, water stress, and nutrient stress. Simulated yield was expressed as total assimilation potential:

$$Y = F_{gass} \times \frac{30}{44} \times FW \times FN \times CVF$$

where F_{gass} is total assimilation rate (kg · hm ²), FW is water stress coefficient, FN is nitrogen stress coefficient, and CVF is photosynthate conversion efficiency.

Water stress coefficient was calculated as:

$$FW = \frac{ET_a}{ET_p}$$

where ET_a is actual evapotranspiration and ET_p is potential evapotranspiration.

2.4 Parameter Inversion

Parameters were inverted using the evolutionary algorithm in Excel' s Solver tool. For Huoquan Station, data from three treatments were combined; for Xiaohe Station, data from two treatments were combined. Inversion included both soil water dynamic parameters and wheat yield simulation parameters.

Soil water dynamic parameters were optimized by minimizing the sum of squared errors between simulated and measured soil moisture:

$$\min \sum_j SW_j = \sum_j \sum_i^{p_j} (\theta_{ij} - \theta'_{ij})^2$$

Crop growth and yield parameters were optimized by minimizing the sum of squared errors for aboveground dry matter (leaves, stems, grains):

$$\min \sum_j SY_j = \sum_j \left[\sum_o^{e_j} (YE_{oj} - YE'_{oj})^2 + \sum_q^{g_j} (YJ_{qj} - YJ'_{qj})^2 + \sum_v^{l_j} (YL_{vj} - YL'_{vj})^2 \right]$$

2.5 Evaluation Metrics

Simulation accuracy was evaluated using: - Regression standard error (RMSE) - Relative error (RE) - Correlation coefficient (r)

For yield simulation with limited data points, relative error was used, and F-test was applied to assess differences among moisture stress response functions.

3. Results

3.1 Soil Moisture Dynamic Simulation

Inverted soil hydraulic parameters showed no significant differences across the three moisture stress response functions, with all values within reasonable ranges (Table 2). Saturated water content exceeded field capacity but remained below porosity, confirming parameter validity.

Soil moisture simulation results (Table 4) showed all three functions achieved highly significant correlations with measured data (minimum r = 0.7814). RMSE values ranged from 0.0217 to 0.0363, indicating excellent agreement. At Huoquan Station, VG function performed best (average RE = 6.37%), followed by LS (7.18%) and MP (8.26%). At Xiaohe Station, errors were generally larger (maximum 12.47%), likely due to neutron probe calibration errors. The VG function again showed the smallest relative error.

3.2 Transpiration and Evapotranspiration Simulation

Moisture stress response functions significantly affected transpiration (T_a) and evapotranspiration (ET_a) simulations (Table 5). The VG function produced values closest to measurements calculated by water balance method. At Huoquan Station, simulated ET_a for zero-water treatments generally exceeded measured values, possibly due to unaccounted deep soil water replenishment. For irrigated treatments, simulated ET_a was typically lower than measured, as high moisture content after irrigation increased downward water movement.

3.3 Yield Simulation

All three moisture stress response functions achieved high-precision yield simulations with correlation coefficients above 0.95 (Table 6). Average relative errors were 8.73% (VG), 8.40% (MP), and 8.42% (LS). F-test results showed no significant differences among functions (F < F_{critical}), indicating that moisture stress response function form did not substantially affect final yield simulation. This is attributed to parameter inversion of water and nitrogen stress coefficients, which corrected for differences in transpiration and nitrogen uptake calculations.

4. Discussion

Water is the primary limiting factor for crop growth in arid regions, making moisture stress response functions crucial components of root water uptake models. This study' s proposed LS function effectively avoids rate 突变 issues in piecewise functions and shows good simulation performance, though its stability under varying environmental conditions requires further investigation.

Nonlinear response functions better represent the continuous, gradual nature of crop growth than linear functions. Soil matric potential, being continuous with depth and unaffected by soil layering, proved superior for moisture simulation. The VG function, based on matric potential, outperformed water content-based functions.

While different response function forms didn' t significantly affect yield simulation in this study, this result stems from parameter inversion adjusting for model structural differences. The PS123 model' s framework, which uses actual-to-potential evapotranspiration ratios as stress factors, may mask underlying differences. Future research should consider dynamic crop coefficient variations and their feedback effects on growth and yield simulation.

5. Conclusions

1. All three moisture stress response functions (VG, MP, LS) achieved satisfactory soil moisture and yield simulations with RMSE values of 0.021-0.036 and correlation coefficients above 0.78. Soil moisture simulation errors averaged 6.37-12.47%, while yield simulation errors averaged 8.40-8.73%.

2. For soil water dynamics, S-shaped curve functions outperformed convex-type functions. The VG function showed the smallest errors and most accurate evapotranspiration simulation.

3. No significant differences were observed among the three functions for yield simulation, as parameter inversion corrected for structural variations.

4. The VG function is recommended as a high-precision, simple, and convenient root water stress response function. The LS function shows potential

for improved accuracy but requires further stability analysis.

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