A Dynamic Programming-Based Method for Simulating Cotton Root Length Growth (Postprint)

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Abstract

Crop root growth depends not only on physiological factors but also on ecological environmental factors, and the relationship between soil water environment and crop root growth constitutes one of the theoretical foundations for designing localized irrigation techniques. To further investigate the primary factors influencing cotton root growth, this study developed a cotton root growth model based on root-shoot water balance, integrating a crop coefficient-leaf area relationship model, root length density distribution function, and root water uptake efficiency function, utilizing dynamic programming theory, and validated the model using results from pot-cultured cotton experiments. The results demonstrate that the model incorporates factors affecting root growth, including soil water environment, atmospheric transpiration demand, and leaf area, thereby possessing the capability to reveal the water consumption mechanism underlying root growth. The simulated trend of total cotton root length by the model aligns well with measured results; when multi-year monthly average reference evapotranspiration (ET0) is used as input, the overall simulation error is 15.41%, making it suitable for engineering design applications. Sensitivity analysis of the model indicates that it can effectively reflect the synchrony between cotton root and leaf growth, as well as the water balance relationship between roots and leaves after the onset of the reproductive growth stage. Cotton root growth exhibits higher sensitivity to soil water environment changes than to leaf area variations, which reflects the underlying mechanism of cotton root growth and validates the feasibility of the modeling approach. The research findings of this paper hold significant importance for improving the theoretical framework of irrigation scheduling design in localized irrigation techniques.

Simulation Method of Cotton Root Length Growth Based on Dynamic Programming Theory

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Abstract

Crop root length and soil moisture distribution are important determinants of crop root water uptake potential. Crop root length changes with growth stage, which also requires changes in soil moisture environment. Therefore, establishing a root growth model to predict crop root growth conditions under normal water use has theoretical and application significance regarding the determination of irrigation quota and soil moisture environment indicators, which are required to design appropriate local irrigation technology. However, current root growth simulating models are more suitable for the determination of irrigation quotas of whole irrigation technology. These models, which are mostly statistical, cannot completely reflect the relational mechanisms of the growth of plant root system, crop water use and soil moisture environment. In view of the above and, a root-canopy water balance combined with crop coefficient vs. leaf area relationship model, root length density distribution function and root water uptake efficiency function, a cotton root growth model was developed based on dynamic programming theory and verified by experimental results of a barrel-cultivated cotton. The main results of the study showed that the model well accounted for the effects of root growth factors such as soil moisture environment, atmospheric transpiration rate and leaf area, which revealed to a certain extent the mechanism of crop water use due to root growth. The growth characteristics of cotton root length simulated by the model were consistent with measured dates in the barrel experiment. When multi-year average monthly mean reference evapotranspiration (ET0) was used as input condition, the overall error of the simulation result was 15.41%. Therefore the model was applicable in engineering designs. Based on sensitivity analysis, the established model well reflected the synchronization between the growth of cotton root and leaf, as well as the water balance between root and leaf after entering the reproductive period. The sensitivity of cotton root growth to changes in soil moisture environment was higher than to changes in leaf area, reflecting the processes of cotton root growth and the feasibility of the modeling method. The research significantly improved the design theory of irrigation systems for the development of localized irrigation technology.

Keywords
Cotton; Root growth; Water balance; Dynamic programming

Introduction

The distribution and growth process of crop root systems are topics of considerable interest in crop physiological ecology, cultivation, and irrigation research, particularly in the design of localized irrigation technology where root distribution and growth determine the effective soil wetting zone. Consequently, scholars have conducted extensive research on crop root growth processes [1–4]. Numerous studies have shown that root weight in most crops follows an "S-shaped" growth pattern through growth stages: slow increase in early stages, rapid growth, reaching maximum in mid-to-late stages, then decreasing, making the entire process similar to a Gaussian distribution. Some crops show slow rather than decreasing growth in later stages, following a Logistic model [2,5–6]. Root length growth also exhibits "S-shaped" characteristics [1,6–8] with a parabolic growth rate [5,7]. Research on cotton (*Gossypium* spp.) root growth [9–14] has demonstrated that both root length and weight follow "S-shaped" patterns. Under favorable soil moisture conditions, root length growth follows a Logistic model, while under water stress it approximates a Gaussian distribution. These findings have greatly advanced understanding of crop root growth patterns and formed the basis for numerous root growth models [2,12,15–16], many of which describe root distribution along soil depth [2,12], revealing that root length density decreases exponentially with depth—higher near the surface and decreasing with depth. Such models are relatively mature, primarily based on the balance principle between canopy transpiration and root water uptake. However, few mathematical models describe root growth across growth stages. Fractal theory-based approaches using differential L-systems have achieved good results in modeling root geometry and simulating root length growth [8,15], while artificial neural network theory has been used to establish stage-based root length models for mulched drip-irrigated cotton, yielding Logistic model results consistent with experiments [13]. Nevertheless, these simulation results are primarily based on statistical methods that largely ignore ecological environmental effects during crop growth and fail to reflect mechanistic relationships between root growth, water consumption, and soil moisture environment, making environmental prediction of root growth difficult. Traditional irrigation scheduling theory considers only root distribution along soil depth when determining irrigation quotas, neglecting root length status at different growth stages—a clear theoretical deficiency for localized irrigation design. Statistical root growth models rarely consider root water consumption factors. Therefore, establishing a crop root growth process model based on root-canopy water balance principles can improve and supplement the theoretical basis for irrigation quota determination in localized irrigation technology. This study employs virtual root research methods [17] and dynamic programming theory based on the balance principle between canopy transpiration and root water uptake to establish a model for cotton root length growth under drip irrigation conditions, providing a reference for root growth simulation research.

1.1 Basic Model

Crop root growth is controlled not only by soil moisture environment but also by canopy water evapotranspiration intensity [18]. Most root water uptake models in academia are based on the balance theory between canopy transpiration and root water uptake [1-2], and it is widely accepted that root dry matter growth rate is proportionally related to canopy growth rate at different stages [12], implying a certain degree of synchronization between root and canopy growth. Therefore, this study utilizes Bellman' s dynamic programming theory [19] to derive root length growth from canopy transpiration processes based on water balance principles. According to Bellman' s dynamic programming theory, each step of the root growth process should follow the principle that water uptake rate equals canopy water consumption intensity, with roots actively growing in easily accessible soil wetting zones—i.e., secondary root segments actively seek optimal soil moisture, temperature, and fertilizer environments. Assuming no spatial variation in soil temperature and fertilizer environments, root growth is affected only by soil moisture environment.

The basic model is defined as: ET(t) is crop canopy transpiration intensity (mm · d ^{1}); Sr(t) is root water uptake rate (mm · d ^{1}); and t is days after emergence (d). ET(t) can be measured directly or calculated from reference crop potential evapotranspiration using the formula where Kc is the crop coefficient dependent on leaf area; K is the soil coefficient dependent on soil moisture status (1 in the simulated wetting zone where moisture stress is minimal); and ET is reference crop potential evapotranspiration representing atmospheric evaporative demand, estimated by the Penman-Monteith formula. For design of soil irrigation wetting zone parameters, multi-year average or specific meteorological frequency values should be used.

The state transition equation is: where Sr(t+1) is the root water uptake rate at the next step; LA is crop leaf area (cm^{2}); (t) is root water uptake efficiency (water flux per unit root length, mm · m ^{1}); V is soil volume occupied by roots; ΔL(t+1) is root length increment at the next step (m · d ^{1}); and t is days after emergence (d).

1.2 Crop Coefficient

Under conditions without soil water stress during main growth stages, crop coefficient and leaf area index have an approximately linear relationship, while leaf area index follows an "S-shaped" curve [20]—slow initial increase, rapid growth during vegetative stages, maximum at peak vegetative growth, then gradual decline due to senescence and leaf drop. Thus, leaf area change over time can be approximated by a Gaussian model. Mu et al. [21] observed a power function relationship between cotton crop coefficient Kc and leaf area index LAI under mulched drip irrigation. Since LAI is positively correlated with leaf area LA [22], this study establishes a relationship model between Kc and individual plant leaf area LA.

Wang et al. [23] observed that leaf area growth is slow before budding, fastest from budding to flowering, peaks during boll development, then gradually declines due to lower leaf senescence and abscission. Therefore, individual cotton plant leaf area over the entire growth period follows a Gaussian curve, and the leaf area-time relationship model used in this study is: where a, b, and c are model coefficients.

1.3 Root Length Density Distribution Function

Assuming constant soil volume V occupied by roots, root length density distribution is uniform within V at any time, changing only with growth time. Numerous experimental results [10,11,14] show that cotton root length density dynamics follow an "S-shaped" curve. Under favorable soil moisture, temperature, and fertilizer conditions, this follows a Logistic model [14]; if water stress occurs in late growth (generally after boll opening), it follows a Gaussian model [11].

Logistic model:
Gaussian model: where dlr(t) is root length density (m · m ^{3}); V is soil volume occupied by roots (m^{3}); and a, b, c are model coefficients.

1.4 Root Water Uptake Efficiency Function

Root water uptake efficiency depends on relationships between water uptake, root distribution, surface area, and root permeability [24], all of which change with growth stage. Under specific conditions, this can be simplified as the ratio of crop water consumption to root length. At seedling stage, limited roots supply canopy water demand, resulting in high efficiency. As root length density increases, more roots share the demand, decreasing efficiency. In later stages, reduced canopy water consumption causes efficiency to drop substantially. Therefore, the relationship between root water uptake efficiency and growth time is a downward-opening parabola. Based on this, the following model is established: where (t) is root water uptake efficiency (mm · m ^{1}); t is days after emergence (d); and a, b, c are model coefficients.

1.5 Model Solution Constraints

The constraints are: where LAm is maximum individual plant leaf area (cm^{3}); dlrm is maximum root length density (m · m ^{3}); is soil water content; f is field capacity; and R is any real number.

1.6 Model Solution Initial Conditions

The initial conditions are: where is the initial leaf area value for model solution (cm^{2}); is the soil volume occupied by roots (barrel volume in this study, m^{3}); is the initial root length density value for model solution (m · m ^{3}); and is the initial root water uptake efficiency value for model solution (mm · m ^{1}).

1.7 Model Solution Procedure

Following dynamic programming solution logic, the solution method for the established model is shown in Figure 1 and implemented using the MATLAB simulation platform.

2. Materials and Methods

2.1 Experimental Materials

The experiment was conducted from May to September 2014 at the Experimental Center of the College of Water Conservancy and Architecture Engineering, Shihezi University (86°03 27 E, 44°18 25 N, altitude 451 m). The cotton variety was ‘Xinluzao 48’ . Barrel specifications were: top inner diameter × bottom inner diameter × height = 45 cm × 35 cm × 53 cm (seedling and budding stages) and 48 cm × 37 cm × 55 cm (flowering, boll, and boll opening stages). The soil was sandy loam, air-dried, crushed through a 2 mm sieve, and packed in layers with dry bulk density of 1.39 g • cm^{3}, porosity of 46.14%, and field capacity (volumetric water content) of 26.06%. One cotton plant was planted per barrel with surface mulching. The experiment initially designed 4 replicates each for seedling, budding, and flowering stages, but root sampling revealed that complete replication sampling was unnecessary. Seedling stage sampling used 1 replicate, but root length and density were too small for meaningful modeling, so remaining replicates were retained for budding stage sampling based on literature experience [25]. Budding stage sampled 3 replicates, flowering stage 4 replicates, and boll and boll opening stages 2 replicates each.

Growth stage definitions and sampling times were: **Seedling stage**–from emergence to budding (approximately 45 days), with root sampling at 40 days after emergence; **Budding stage**–when the first triangular bud (3-5 mm) appeared on the first fruiting branch, with root sampling at 56 days after emergence (11 days after budding, peak budding stage); **Flowering stage**–when the first flower opened on any basal fruiting branch, with sampling at 76 days after emergence (10 days after flowering, peak flowering stage); **Boll stage**–when the first boll (>2 cm diameter) appeared on the first fruiting branch, with sampling at 102 days after emergence (10 days after boll formation); **Boll opening stage**–when the first boll opened, with sampling at 130 days after emergence (15 days after boll opening).

Irrigation amounts per barrel were: seedling stage 1 L, budding stage 2 L, flowering-boll stage 3 L, and boll opening stage 2 L. To prevent rapid water infiltration along barrel walls, a 30 cm diameter waterproof paper ring was buried 5 cm deep in the soil surface. Rain protection measures were taken during precipitation to ensure treatment effectiveness.

2.2 Measurement Methods

Soil moisture vertical distribution was measured by oven-drying method before and after irrigation. To minimize root damage, soil samples were taken at 15 cm from the cotton plant using a 2 cm diameter auger at 10 cm depth intervals to the barrel bottom, with 3 barrels sampled each time, and refilled with sieved, air-dried soil of the same texture.

Leaf area measurements began 10 days after emergence at 10-day intervals, with additional measurements on root sampling days. Single leaf length and width were measured using a millimeter-scale ruler with the cross method, measuring all expanded leaves (excluding yellow and unexpanded leaves). Leaf area was calculated using LA = • X • Y [26] (LA: leaf area; : coefficient; X: leaf length; Y: leaf width), with = 1 in this experiment.

Root distribution parameters were obtained using the bidirectional slicing method [27] at each growth stage. Roots were sampled in 10 cm × 10 cm × 10 cm cubes centered on the cotton plant in horizontal and depth directions to the barrel edge and bottom. Root samples were extracted, washed clean, spread on graph paper, photographed, vectorized using R2V software, processed with Office Access 2003, and average root length density per plant was calculated.

2.3 Results and Analysis

Model validation used canopy transpiration converted from reference crop potential evapotranspiration ET calculated by the Penman-Monteith formula. Multi-year monthly average ET values for Shihezi (1981–2010) are shown in Table 1 .

Since leaf area growth follows a Gaussian model and previous research including the GOSSYM cotton growth simulation model [12] shows that root-to-shoot dry weight ratios approximate different constants at various growth stages—indicating synchronized root and canopy growth—root length density dlr in the simulation used the Gaussian model, with root volume V as barrel volume. Seedling stage roots were too small with negligible density, so only data from pre-budding and later stages were compared. Other model coefficients were fitted from experimental data, with results shown in Table 2 .

Comparison between simulated and measured results is shown in Figure 2 [Figure 2: see original paper]. The data show rapid root length growth from pre-budding to flowering (40–80 days after emergence), reaching maximum at boll stage (~100 days), then declining after boll opening (~110 days). The simulated trend generally matches measured values, though simulated values are lower than measured values during 42–83 days (budding and flowering) and after 120 days (boll opening). This occurs because ET used multi-year monthly averages, which may be lower than actual values during these stages, resulting in lower calculated leaf transpiration and slower simulated root growth. However, this ET selection is reasonable for engineering design [28].

Additionally, simulated root length decline during boll opening is faster than measured because: (1) ET effects during simulation, and (2) the assumption of uniform root length density distribution in space. When leaf water consumption decreases during boll opening, fewer absorbing roots are needed, causing synchronous reduction of root length throughout the space. Measured results show non-uniform distribution—root length density first increases then decreases with depth; horizontally maximum at the root axis with symmetric distribution on both sides; obvious attenuation in dense root zones due to competition; less attenuation in sparse zones, resulting in smaller overall decline than simulated values. The model reflects root growth responses to soil moisture environment, atmospheric transpiration, and leaf area, revealing the water consumption mechanism of root growth.

3. Model Sensitivity Discussion

Relative error between calculated and measured values follows a pattern of first increasing, then decreasing, then increasing again during simulation, with maximum relative error (26.19%) at 56 days after emergence (budding stage, when leaf area and root length density growth accelerate) and minimum error (4%) at 102 days (boll stage). Overall error is 15.41%, which meets engineering design accuracy requirements (10%-20%), indicating model effectiveness.

In the dynamic programming model, state variables leaf area LA and root length L are both functions of growth time t. Under the same time change Δt, relative change in leaf area always exceeds that in root length. Literature [29] suggests that crop growth focuses on roots in early stages (root growth faster than leaf growth), shifts to canopy in reproductive stages (leaf growth faster than root growth), then both slow in late stages. This indicates the established cotton root length growth model appropriately reflects root-leaf water balance relationships during reproductive growth, where root growth responds to changing root-leaf water balance.

The model involves four state variables affecting results: crop coefficient Kc, leaf area LA, root length density dlr, and root water uptake efficiency (t), but only LA, dlr, and (t) have degrees of freedom. Using barrel experiment results as control, each variable was varied by -15% to assess impact on simulation results, calculated by: where p is impact percentage (%); X is the state variable with degrees of freedom; LΔ-15% is simulated total root length after -15% variation; and LΔ0% is simulated total root length without variation.

Results show that -15% variation in leaf area LA and root length density dlr both reduce simulated root length (Figure 3 [Figure 3: see original paper]), but leaf area impact (mean -13.9%) is less than root length density impact (mean -14.9%). Leaf area impact remains nearly constant throughout growth stages, while root length density impact varies—smaller in early stages, larger in late stages, becoming almost direct after 100 days (boll stage). This reflects three aspects: (1) Positive correlation between root and leaf growth, consistent with literature on “cotton root-shoot growth synchronization” [12], reflecting physiological balance between leaf transpiration and root water uptake; (2) Although root length density and root growth are positively correlated, the causal relationship is that root growth affects density distribution, especially under barrel conditions (or limited wetting space)—early root growth has sufficient space with slow density increase, while mid-to-late growth approaches spatial limits, forcing secondary and tertiary lateral roots to grow in the wetting zone, directly increasing density; (3) Greater sensitivity of root growth to soil moisture environment than to leaf area changes conforms to general root growth patterns [2].

Under water balance conditions, unit root length water uptake rate determines total root length needed to maintain balance. When root water uptake efficiency (t) varies by -15%, simulated root length increases (mean impact 17.6%) with nearly constant effect throughout the growth period (Figure 3 [Figure 3: see original paper]), indicating negative correlation between efficiency and root length—lower efficiency requires more roots to maintain water balance.

Comparing absolute impact values, root water uptake efficiency affects cotton root length growth more than canopy water consumption and root length density (or soil moisture environment). Therefore, reasonable fertilization and increased soil temperature to improve root water uptake efficiency can promote crop root and plant growth [2]. For cotton root growth, leaf area and soil moisture environment are external factors, while root water uptake efficiency is internal, thus having the greatest impact.

Previous cotton root length growth models were primarily statistical [23], not reflecting root-leaf or root-soil water environment physiological-ecological relationships, yet leaf water consumption and soil moisture environment are precisely the boundary conditions constraining root growth. The dynamic programming model based on water balance principles incorporates these constraints, giving it mechanistic properties. Although state variables still use statistical time functions, the model structure reflects effects of leaf water consumption, soil moisture status, and root space on cotton root length growth. While substantial research exists on cotton leaf growth and root length density changes, root water uptake efficiency research needs enrichment, making this modeling method helpful for irrigation technology design.

Conclusions

1) Under conditions without water stress during main cotton growth stages and with all roots absorbing water, this study established a cotton root length growth model using dynamic programming theory based on water balance principles. Barrel experiment validation showed simulated root length growth generally consistent with measured results. Using multi-year monthly average ET as input, overall simulation error was 15.41%, making the model effective for determining effective soil wetting zones in

localized irrigation technology design.

2) The model reflects synchronization between cotton root and leaf growth and the water balance relationship after entering reproductive stages. For external factors affecting root growth, simulation results show cotton root growth is more sensitive to soil moisture environment changes than to leaf area changes, indicating the model can reflect mechanistic relationships between cotton root growth, canopy water consumption, and soil moisture environment, and that the modeling approach is feasible.

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