Simulating Root Growth Dynamics of Cowpea Under Varying Soil Conditions

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Abstract We present a simple root growth model that is capable of reproducing root distribution patterns as conditioned by varying soil conditions. The model considers the lateral growth of roots at any depth as logistic, and is governed by two factors: (i) the current root mass or root length density at a given depth, and (ii) an environmental factor that may limit the further growth of roots at that depth. Using the relative soil water content as the environmental factor, it is shown that an exponentially declining root distribution, commonly observed under wet soil profiles can be reproduced by the model.. Other non-exponentially declining root profiles observed under spatially varying soil water contents can be simulated. The results indicate that the simple root model is capable of predicting differing root growth and distribution patterns, consistent with empirical observations under varying soil conditions.

1. INTRODUCTION

The role of roots in the transfer of water through the soil-plant-atmosphere system and as the agents for nutrient uptake by crops, has been recognised for many years. But, both the study of root growth and the estimation of root growth dynamics in the soil lags behind comparable studies of the above ground growth [Gregory et al., 1978]. Invariably, root growth modelling continues to be the weakest part of many crop models [Ritchie and Godwin, 1989]. Much of the current approach to root growth modelling assumes a declining root distribution with depth either exponentially as noted by Gewitz and Page [1974] or as an inverse square root function of depth [Monteith et al., 1989].

Other patterns of root growth and distribution patterns have been observed as a result of varying soil water content [Klepper et al., 1973], soil strength [Chan and Mead, 1992] or soil nutrients [Drew et al., 1973]. The exponentially declining patterns appear to represent only situations under which soil conditions are optimum for root growth. A root growth model must be capable of reproducing the varying patterns as conditioned by varying environmental resources. Such a model also needs to incorporate the dynamical processes affecting the root growth under varying environmental conditions. The focus of this paper is to present a simple root growth model that satisfies this condition.

2. MODEL FRAMEWORK

2.1 Root:Shoot Partitioning

Following Montieth et al., [1989], our root model is linked to the overall plant growth. If ΔW_g is the increase in the overall crop dry matter (kg m^{-2}) in the time interval Δt (s) and X_r is the fraction of dry matter allocated to the roots within the same time interval, then the increase in root growth, ΔW_r, (kg m^{-2}) may be obtained from:

$$\Delta W_r = X_r \, \Delta W_g. \tag{1}$$

Further, by assuming a constant root length: root weight ratio, c (m kg^{-1}), ΔW_r may be converted to the increment in root length, ΔR_{Lt}, as:

$$\Delta R_{Lt} = c \, \Delta W_r \; (m \; m^{-2}). \tag{2}$$

ΔR_{Lt} is the sum of the increment in root length at all depths and in all possible directions and not only the increase in root length at the bottom of the rooting depth. The current root depth, *Rtdep*, at any time is obtained by considering that the root front extends into the soil at a constant velocity, *rfv* (m/d), such that:

$$Rtdep(t) = Rtdep(t-1) + rfv. \tag{3}$$

2.2 Distribution of the Newly Partitioned Root Length

The determination of the manner in which the newly partitioned root length is distributed over the current rooting depth requires the description of biological and environmental factors that determine root growth at each soil depth. These issues have been considered in some earlier works such as Hillel and Talpaz [1976].

The recent work of Adiku et al., [1995a], proposed a simple framework suggesting that the rate of increase in current local root growth, $R_L(z,t)$ at any depth, z, is governed by three main factors (i) the current root length at that depth, (ii) the closeness of the current root length at that depth to the carrying capacity R_{Lmax} for roots, and (iii) an environmental factor or modifier, $E_f(z,t)$. The root growth equation at any depth is then was given by :

$$\frac{dR_L(z,t)}{dt} = R_L(z,t).P_r[1-\frac{R_L(z,t)}{R_{L\ max(z)}}].E_f(z). \quad (4)$$

where P_r is the relative growth rate.

Note that (4) may be integrated immediately provided that R_{Lmax} and $E_f(z,t)$ are independent of time. Where R_{Lmax} and $E_f(z,t)$ are constants, the root profiles are logistic curves, indicating that root growth at any depth will eventually stop once the carrying capacity is reached.

Although we lack empirical support at this stage of model development, we conjecture that R_{Lmax} itself would also be affected by the environmental factors. Under high water stress for instance, it is conceivable that the carrying capacity would decrease. While we note that some further research is needed in this area, the inclusion of this effect in our model will be straight forward.

Considering the soil water content as the environmental modifier, we express E_f(z,t) in a non-dimensional form:

$$E_f = 1;\ \theta_c < \theta < \theta_u \quad (5)$$

$$E_f = \frac{\theta-\theta_L}{\theta_c-\theta_L};\ \theta_L < \theta < \theta_c \quad (6)$$

and

$$E_f = 0;\ \theta < \theta_L \quad (7)$$

where θ_u is the field capacity soil water content, θ_c is some defined water content below which the water stress factor declines linearly until it reaches zero at a lower limit θ_L.

The soil water content at any depth and time (θ(z,t) is obtained as an output from a water balance model that solves the water flow equation numerically. Root water extraction at any depth is included as a distributed sink term, S:

$$\frac{\delta\theta}{\delta t} = -\frac{\delta J_w}{\delta z} - S(z,t) \quad (8)$$

where J_w is the flux of water (m/s).

The maximum sink strength at any depth and time is determined from the current local root length, the maximum uptake per unit root length, q_r, (m3/m) and a water stress factor (expressed similar to E_f(z,t):

$$S(z,t) = R_L(z,t).q_r.E_f(z,t) \quad (9)$$

The daily water extraction from the soil depends on the potential transpiration which is estimated using the concept of transpiration ratio [Monteith et al., 1989]. To determine the actual water extraction at each depth, the soil profile is searched from the top to the current root depth. So long as the potential transpiration is not met at any depth, the actual uptake from that layer is taken as the minimum of the sink strength and the potential transpiration. Any water deficit is satisfied from the next layer and the process continues until the requirement for the day is satisfied.

However, if upon searching through the current rooting depth the daily water requirement is not satisfied, the overall growth of the crop is limited by a stress index calculated as the ratio of actual to potential transpiration. Hence, there is a feedback between soil and plant growth processes.

Now (4) represents the demand that the roots at each depth make on the total ΔR_{Lt}, within a time interval Δt. Call this $w_f(z,t)$. By summing $w_f(z,t)$ over all depths, we obtain the total demand:

$$D = \int_{c_1}^{Rtdep(t)} w_f(z,t)dz. \quad (10)$$

where c_1 is the sowing depth (m).

This demand may or may not be met by the incoming ΔR_{Lt}. In the absence of any information on preferential allocation by the plant itself, we assume that the allocation of the newly partitioned root mass to any depth is in proportion to the relative demand at depth z, given by:

$$rwf(z,t) = \frac{w_f(z,t)}{D} \quad (11)$$

Consequently, the actual increase in root length at depth z, is:

$$\Delta R_L(z,t) = rwf(z,t).\Delta R_{Lt}. \quad (12)$$

Note that the relative demand is affected by the current root length at depth z, and the environmental factor, as previously discussed.

At any depth, the increment in the local root length may be converted to increase in root length density, $\Delta R_{Lv}(z,t)$, by dividing by the appropriate soil element volume. The root length density at a given depth z and time t is then calculated from:

$$R_{Lv}(z,t+\Delta t) = R_{Lv}(z,t) + \Delta R_{Lv}(z,t)\ (m\ m^{-3}). \quad (13)$$

3. MATERIALS AND METHODS

The framework outlined above for modelling root growth and distribution was programmed in FORTRAN 77 and coupled to a cowpea model by Adiku et. al., [1995b] which runs on a daily time step. The necessary data required to simulate root growth include the root front velocity, (taken as 0.033m/d); the maximum root length density (R_{Lvmax}, 3 x 10^4 m/m ^{3} ; Robertson et al., [1980]) and the root dry matter partition co-efficient, X_r, which was varied from 0.4 at emergence to 0.1 at flowering and the root dry weight:root length ratio, c, (taken to be 6.5 x 10^4 m kg^{-1}; Boote et al., [1987]).

The soil profile was 1.50m deep and was assumed to consist of layers of 0.05m thick.

3.1 Simulation Experiments

Root growth and distribution profiles were simulated during the growth of a cowpea crop under four scenarios. First, cowpea was grown on an initially full profile under full scale irrigation that ensured non-limiting water conditions throughout the whole growing season. To achieve this, the $E_f(z,t)$ was set to unity at all depths and times. Second, cowpea was under similar initial conditions as in the first scenario except that only the top 0.3m was considered to be non-limiting in soil water so that Ef(z,t) was set to unity from the soil sueface to this depth.

Third, cowpea grew on stored water from an initially wet profile and underwent a drying cycle through the whole growth duration. Finally, the cowpea crop was grown on stored water as was in scenario three but with an initially dry top soil (the initial water potential of the top 0.3m was set to −7 bars.

4. RESULTS AND DISCUSSION

Fig 1a. shows the simulated distribution of cowpea root with depth for the conditions specified in the first scenario. It is evident that the typical exponentially declining distribution commonly observed under non-limiting resource conditions has been reproduced for the times 10, 20, 30, 45 and 60 days after cowpea planting. The exponential equation fitted to the distribution on day 60 gave a decay coefficient of 1.9 and the fit was good (R^2= 0.992).

Note that in accordance with (4) with $E_f(z,t) = 1$, the only determinants of root growth at any depth is $R_L(z,t)$ and time. Since root growth begins at the top soil layer, then growth would be occurring at the upper parts of the profile for longer periods of time than at the lower depths. Consequently, more root dry matter will accumulate at those zones before the root front reaches greater depths.

Further, the weighting of root growth in proportion to the current root mass would also result in much more dry matter accumulation at the upper parts of the profile. Also evident is the self-limiting increase in root length density as the carrying capacity is approached. The highest root length density (R_{Lv}) simulated was about 2.91 x 10^4 m m^{-3} (Fig. 1a) at a depth of 0.05m at 60 days after planting (DAP).

Fig. 1b shows the simulated patterns of root distribution during the second scenario. The patterns follow closely those observed for the first scenario except that the decay coefficient was slightly higher, indicating relatively more root growth in the upper parts of the soil profile. It is conceivable that should the subsoil be much drier initially, the decay coefficient would be much higher.

Fig. 1c shows the simulated distribution of cowpea roots for the third scenario. Two aspects of the root growth stand out clearly. First, the overall growth of the roots was inhibited as the plant grew under considerable water stress. The maximum root length density did not exceed 0.6 x 10^4 m^{-3}, unlike the previous situations. Except for 10 DAP, the distribution cannot be generally described by any simple exponentially decay equation. The final root profile at 60 DAP suggests a more uniform distribution with depth.

Simulations of root distribution for the final scenario are similar to that observed for the third (Fig. 1d). Noteworthy is that much more root growth occurred in the subsoil than at the upper parts of the profile. In other words, a thin drying surface layer with high water stress will permit a faster growth of roots in the lower wetter layer.

These observations indicate that the concept presented in this work for modelling root growth and distribution with depth is quite sound. We may mention that although the only soil factor considered was water content, the effects of the other factors such as nutrients and soil strength could be expressed in the same manner.

We emphasise unlike other root models that assume an exponential decay, our approach allows the attainment of the maximum root length density at any depth. Thus when root growth in the top layers is restricted by water stress or otherwise, a compensatory increase in root growth in deeper layers can occur provided the subsoil has less water stress. Second, the different root distribution patterns are determined by the spatial patterns of stress factors in the soil environment, and not by the choice of a decay constant.

Further, even if the root front velocity is not constant but is affected by soil water status as may happen when the soil strength increases with decreasing soil water content, this effect can be handled numerically in our model.

5. CONCLUSION

We present a simple framework for modelling root growth and distribution with depth. Factors considered in the model include both biological growth parameters as well as environmental modifiers.

Results from the simulation studies indicate that real observations were well mimicked by the model and therefore suggests that the modelling concepts are quite sound.

The model structure is generic and allows the inclusion of several other environmental factors. By formulating the effects as weighting factors, there is no need to determine the absolute values of root growth parameters such as proliferation rate.

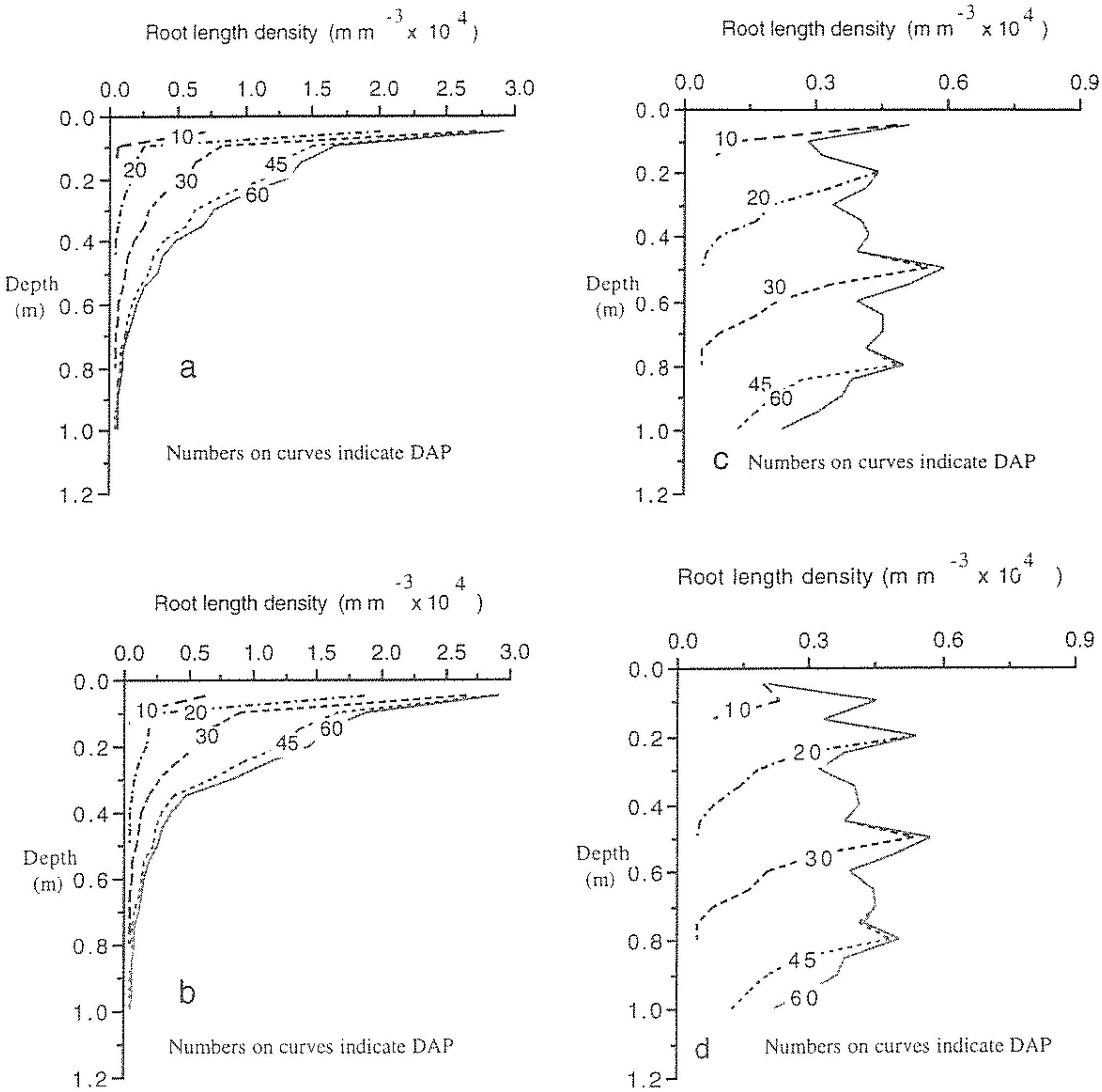

Fig. 1. Simulated root distribution patterns of a cowpea crop under varying soil water conditions: (a) fully irrigated profile; (b) initially wet but with only the top 0.3 m replenished with water; (c) drying cycle of an initially wet profile; (d) drying cycle but with top 0.3 m initially drier.

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