Modelling the effect of varying soil water on root growth dynamics of annual crops

S.G.K. Adiku¹, R.D. Braddock and C.W. Rose

Faculty of Environmental Sciences, Griffith University, Brisbane, QLD, Nathan 4111, Australia.
¹Present address: Department of Soil Science, Faculty of Agriculture, University of Ghana, Legon, Accra, Ghana, West Africa

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Abstract

We present a simple framework for modelling root growth and distribution with depth under varying soil water conditions. The framework considers the lateral growth of roots (proliferation) and the vertical extension of roots (root front velocity). The root front velocity is assumed to be constant when the roots descend into an initially wet soil profile. The lateral growth of roots is governed by two factors: (1) the current root mass or root length density at a given depth, and (2) soil water availability at that depth.

Under non-limiting soil water conditions, the increase in root mass at any depth is governed by a logistic equation so that the root length density \( R_v \) cannot exceed the maximum value. The maximum \( R_v \), is assumed to be the same for all depths. Additional dry matter partitioned to roots is initially distributed according to the current root mass at each depth. As the root mass approaches the maximum value, less dry matter is partitioned to that depth.

When soil water is limiting, a water deficit factor is introduced to further modify the distribution of root dry matter. It is assumed that the plant is an “energy minimiser” so that more root mass is partitioned to the wetter regions of the soil where least energy will be expended for root growth. Hence, the model allows for enhanced root growth in areas where soil water is more easily available.

Simulation results show that a variety of root distribution patterns can be reproduced due to varying soil water conditions. It has been demonstrated that broad patterns of root distribution reported in the literature can also be simulated by the model.

Introduction

In conventional studies of crop production, the importance of water transfer from the soil through the plants to the atmosphere has long been recognised. Roots are the agents for water and nutrient uptake and on decay, become important nutrient sources especially at greater depths. The study of root growth in relation to soil conditions has, however, advanced less rapidly than comparable studies of the above ground parts of the plant (Gregory et al., 1978). This apparent lack of progress has been partly attributed to the difficulties in observing root growth and the effort in obtaining satisfactory root measurements.

Similarly, there have been fewer efforts to model root dynamics compared with modelling of the above ground growth of crops. It has been recognised that in general, the modelling of the below-ground growth continues to be the weakest part of many crop models (Ritchie and Godwin, 1989). To improve root growth modelling will require the consideration of those factors that affect both dry matter partitioning to roots and the distribution of this dry matter with depth.

We recall the conventional approach to describing root distribution with depth, following Gewitz and Page (1974),

\[
R_v(z) = \alpha \exp(-\beta z),
\]
where \( R_v(z) \) is the root length density (m \( m^{-3} \)) at depth, \( z \) (m), below the soil surface, and \( \alpha \) and \( \beta \) are constants. Equation (1) describes a root distribution which declines exponentially with soil depth. Such patterns of root distribution with soil depth have been observed by several researchers (Feddes and Ritjema, 1972; Gregory and Reddy, 1982) and are often used as a basis for predicting root growth in many crop models (e.g. CERES maize; Jones and Kiniry, 1986). Nevertheless, such patterns of root distribution are typically observed only when roots grow in uniform soils under non-limiting resource conditions.

Under less than optimum soil water conditions, considerable departures from Equation (1) have been observed. Malik et al. (1979) showed deep roots of cotton growing about 8 times as fast when the surface soils were maintained at only 20% of saturation as compared to when the surface was at 50% of saturation. By altering irrigation schedules, Klepper et al. (1973) were able to stimulate a maximum root length density in cotton at a depth of about 1.8 m, in a drying soil profile. However, under well watered conditions, the typical exponential decline of root density with depth was still observed in cotton with the highest root densities occurring at about 0.2 m depth. Other factors such as the soil strength which depends on soil water content, can also exert a large influence of root growth (Chan and Mead, 1992).

Obviously the allocation of dry matter partitioned to various parts of a root system is affected by soil water conditions so this must also be considered in modelling root distribution. A recent attempt was made by Robertson et al. (1993) to incorporate soil water content into their model of root growth. However, their model was still based on root patterns given by Equation (1) so only an exponentially decreasing \( R_v \) with soil depth could be obtained.

In this paper, we present a framework for modelling root growth and its distribution with depth under varying soil water conditions. Our model attempts to overcome some of the shortcomings of earlier models by including a soil water content factor as an environmental modifier of root growth and distribution.

**Materials and methods**

**Theory**

Since roots are an integral part of a plant, our root growth model is linked to the growth of the whole plant. Plant growth rate is calculated from light interception according to:

\[
\frac{\Delta W_g(t)}{\Delta t} = Q.e.S,
\]

where \( \Delta W_g(t) \) is the increase in crop dry matter per unit ground area (kg m\(^{-2}\)) in a given time interval, \( \Delta t \) (s), \( Q \) is the proportion of the incident radiation \( S \) (MJ m\(^{-2}\) s\(^{-1}\)) intercepted and \( e \) (kg MJ\(^{-1}\)) is the corresponding radiation use efficiency. \( Q \) can be estimated from:

\[
Q = 1 - \exp(-k.L),
\]

where \( L \) is the leaf area index (m\(^2\) m\(^{-2}\)), \( k \) is the extinction coefficient, and \( e \) in Equation (2) can be estimated according to the procedure described in Charles-Edwards et al. (1986). Hence, \( Q, k \) and \( e \) are crop dependent parameters. A listing of the important variables and parameters is given in the Appendix.

The quantity of dry matter per unit area partitioned to the roots, \( \Delta W_r(t) \) (kg m\(^{-2}\)), in the time interval, \( \Delta t \), is taken to be a fraction, \( X_r(t) \), of the total dry matter produced per unit area (Johnson and Thornley, 1987; Reynolds and Thornley, 1982) and is given by:

\[
\Delta W_r(t) = X_r(t) \Delta W_g(t).
\]

The parameter \( X_r(t) \) is assumed to vary for the different stages of crop growth as explained later.

Assuming a constant root length : root weight ratio, \( c \) (m kg\(^{-1}\)), the increment in the total root length per unit ground area, \( \Delta R_{A,T}(t) \) (m m\(^{-2}\)) can be calculated as:

\[
\Delta R_{A,T}(t) = c.\Delta W_r(t).
\]

We now seek to partition this increase in root growth throughout the root zone.

In partitioning \( \Delta R_{A,T}(t) \) over the current rooting depth, two important aspects of the root system were considered, namely, (i) how far the roots penetrated into the soil in a given time interval and (ii) how soil water conditions influence root distribution.

The literature provides some information on how these issues may be handled. For example, in modelling the growth of sorghum and millet, Monteith et al. (1989) suggested that the size and distribution of the root system can be specified using two parameters: one to describe the rate of vertical extension of the root front (the root front velocity) and the other to describe the rate of lateral proliferation of roots (the root length density).