USE OF A MODEL TO ANALYSE THE ROLE OF TREES IN SOIL WATER DISTRIBUTION AND UTILISATION

Q.Y. PANG*, I. R. JOHNSON, and P. V. LOCKWOOD

Department of Agronomy & Soil Science,
The University of New England, Armidale, New South Wales 2351, Australia

(Received for publication 26 March 1995; revision 28 January 1996)

ABSTRACT

A physically based model was developed to simulate changes in plant water use and soil water distribution over time. It was built from two main submodels which dealt with soil water flow and plant water uptake. The soil water flow submodel employed the Richards equation combined with vapour flow procedures to predict soil water distribution, deep drainage, and soil evaporation. The plant water uptake submodel used a potential driven approach in that it depended on the water potential gradient between the roots and soil matrix. The model was used to analyse the effects of rooting patterns on deep drainage, which is one of the main differences in plant properties between trees and annual crops or grasses. Root distribution affects plant water uptake, soil water distribution, and deep drainage. The deep drainage rate under Armidale (NSW, Australia) weather conditions is episodic in character and root distribution influences deep drainage during wet periods. From discussion of the optimal root distribution for an agroforestry system it was concluded that to prevent too much deep drainage, it may not be necessary to have only deep-rooted species present. Simulation can indicate the appropriate ratio of deep-rooted trees to shallow-rooted crops or grasses in an agroforestry system where the aim is to minimise deep drainage while maximising the percentage of productive shallow-rooted crops or grasses.

Keywords: simulation model; root distribution; deep drainage; agroforestry.

INTRODUCTION

It is well documented that dryland salinity can occur as a result of the water table rising, which follows a change in the water balance when perennial native vegetation is replaced by annual agricultural plants (Peck & Williamson 1987). Agroforestry offers considerable potential to reduce the effects of salinisation due to the influence of trees in preventing deep drainage. However, there is a lack of information, which leads to differences of opinion on basic questions such as which species to plant, where to locate plantings, at which spacing to plant, and how much area to plant (Schofield 1992). To address these problems we need to know how plant properties affect the soil water balance, especially the factors controlling

* Current address: Department of Agricultural & Biosystem Engineering, McGill University, PQ Canada H9X 3V9

deep drainage. One of the differences in plant properties between trees and annual crops or grasses that influences water uptake is root distribution. Measuring root density and distribution is difficult and tedious, so that experimental assessment of their significance is not easy. Also, it is hard to isolate the influence of different processes or plant properties experimentally. Computer modelling offers an alternative and convenient method of exploring this problem, and can provide valuable insights into the underlying processes. This paper describes use of a simulation model to explore the effects of root patterns on soil water distribution, soil water balance, and deep drainage.

MODEL DESCRIPTION AND BEHAVIOUR

The model was developed in order to explore theoretically, at a process level, variation in water loss between crops with different properties. There is a range of modelling routines and equations that may be used to describe the various components of water movement through the soil-plant-atmosphere system. Flexibility was built into the present model to facilitate comparison of the effects of these different approaches on overall model behaviour. The model uses routine daily meteorological data as inputs which are then distributed to hourly series. The outputs include soil water contents in different layers of the soil profile, transpiration, evaporation, and deep drainage.

The driving force for water loss from canopies is potential evapotranspiration (ETP) which is described using the Penman-Monteith equation (*see*, for example, Thornley & Johnson 1990), with the aerodynamic term as formulated by Campbell (1977). Rainfall interception is modelled in a similar way to that used by Persson & Lindroth (1994). Soil water flow and plant water uptake, which are the submodels of most concern in this study, are described here in detail.

Soil Water Flow

Water flow in the soil is described using the Richards equation. This was derived by combining Darcy's law for water movement with the continuity equation. We included liquid and vapour flow. The resulting equation is:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial z}\left[k_w \frac{\partial}{\partial z}(\psi - z)\right] - \frac{\partial}{\partial z}\left[k_v \frac{\partial H}{\partial z}\right] + U \qquad (1)$$

where θ is volumetric water content; t is time; z is soil depth, positive downward; k_w is hydraulic conductivity; ψ is soil water matric potential; k_v is vapour flow conductivity; H is relative humidity, which is a function of soil water potential; U is the rate of root water uptake per unit of soil volume. The equation does not account for preferential flow.

Equation (1) was discretised on a soil depth grid with a backward difference or fully implicit form in time, and solved by the Newton-Raphson iterative method (Campbell 1985). A hyperbolic transfer technique which increases the numerical efficiency was used to make the iteration quicker and to overcome problems arising from initially dry, inhomogeneous soils (Ross 1990).

In order to solve Equation (1), boundary conditions at the soil surface and the lower boundary are prescribed. The upper boundary water flux (infiltration at the soil surface) is set as equal to the rainfall intensity for an unsaturated surface soil layer. For a saturated surface soil layer it is set equal to either the saturated hydraulic conductivity or the rainfall intensity, which ever is least. The remaining rainfall is added to the rainfall input at the next time step. The vapour flux is set to zero at the base of the soil profile being simulated and to actual evaporation at the soil surface. Depending on accuracy requirements, vapour flux can be set off or on. Soil evaporation is calculated from the difference in humidity between the soil at the surface and the atmosphere. The humidity at the soil surface is a function of soil water potential and soil temperature (Campbell 1985). Deep drainage is considered to be controlled by gravity only, which is also a lower boundary condition for the simulations.

Plant Water Uptake

Plant water uptake is described under the assumption that water flow through the soil-plant-atmosphere-continuum (SPAC) is steady (i.e., there is no change in water storage in the plant). Water flow through the SPAC is assumed to be analogous to an electric current flowing through a series of resistors and governed by Ohm's law (van den Honert 1948, cited by Campbell 1985). The water flux through any component of the system is proportional to the difference in water potential at either side of the component and inversely proportional to a resistance term.

The main resistances to water flow through the SPAC are soil resistance, root resistance, stomatal resistance, and aerodynamic resistance. The soil resistance equation adopted in this model was based on a single-root water flow model (Gardner 1960; Cowan 1965; Campbell 1985; Moldrup *et al.* 1992). Root resistance and stomatal resistance were as described by Campbell (1985). All roots were assumed to have the same resistance to water uptake, independent of position, age, or degree of branching. Water potential was assumed to be the same within all roots at a given time.

To calculate root water uptake in each soil layer, it is necessary to calculate the leaf water potential. This is done by numerically solving the following equation:

$$\frac{\Sigma[(y_{si}-z_i)/R_{sri}]}{\Sigma[1/R_{sri}]} - \frac{TP/(1+(\psi_L/\psi_c)^{SP})}{\Sigma[1/R_{sri}]} - (TP/(1+(\psi_L/\psi_c)^{SP}))*R_L - \psi_L = 0 \quad (2)$$

where ψ_{si} is the soil water matric potential in layer i; R_{sri} is the sum of the soil and root resistances in soil layer i; z_i is the soil node depth; R_L is leaf resistance; TP is potential transpiration demand; ψ_L is leaf water potential; ψ_c is critical leaf water potential at which stomatal resistance reaches twice its minimum value; SP is an empirical constant which determines how steeply resistance increases with decreasing potential (Campbell 1985).

The leaf water potential calculated from Equation (2), then is used to calculate root xylem potential, ψ_{xr}, as:

$$\begin{cases} \psi_{xr} = \{-TP/(1+(\psi_L/\psi_c)^{SP}) + \Sigma((\psi_{si}-z_i)/R_{sri})\}/\Sigma(1/R_{sri}) & (\psi_{xr} > \psi_c) \\ \psi_{xr} = \psi_c & (\psi_{xr} < \psi_c) \end{cases} \quad (3)$$

Water uptake in different soil layers, u_i, is then calculated as being proportional to the potential differences between soil water and root xylem and inversely proportional to the soil and root resistances as:

$$u_i = -(\psi_{xr} - (\psi_{si} - z_i))/R_{sri} \quad (4)$$

The transpiration rate is the sum of the plant water uptake in each soil layer.

With a complex model of this nature, it is important to attempt to ensure that the numerical techniques are free of error. To this end, we generated solutions from both the present model and GAPS (General Purpose Simulation Model of the Soil-Plant-Atmosphere System) (Buttler & Riha 1987) (Fig. 1). The plant properties for the simulations were: plant height 1 m; leaf area index 4; root density distribution exponentially declining from a maximum at 0.05 m (0.3×10^4 m/m^3) to zero at 1 m. The soil parameters were: saturated hydraulic conductivity 0.85×10^{-3} kg/s/m^3, air entry potential –1.47 J/kg, soil B value* 5, and saturated water content 0.5 m^3/m^3. Initial soil water contents were 0.3 m^3/m^3 . Meteorological data were from Armidale, NSW, in 1983. There is good agreement in the change of soil water volume and drainage between the two models, providing evidence for the validity of the numerical techniques used in the present model.

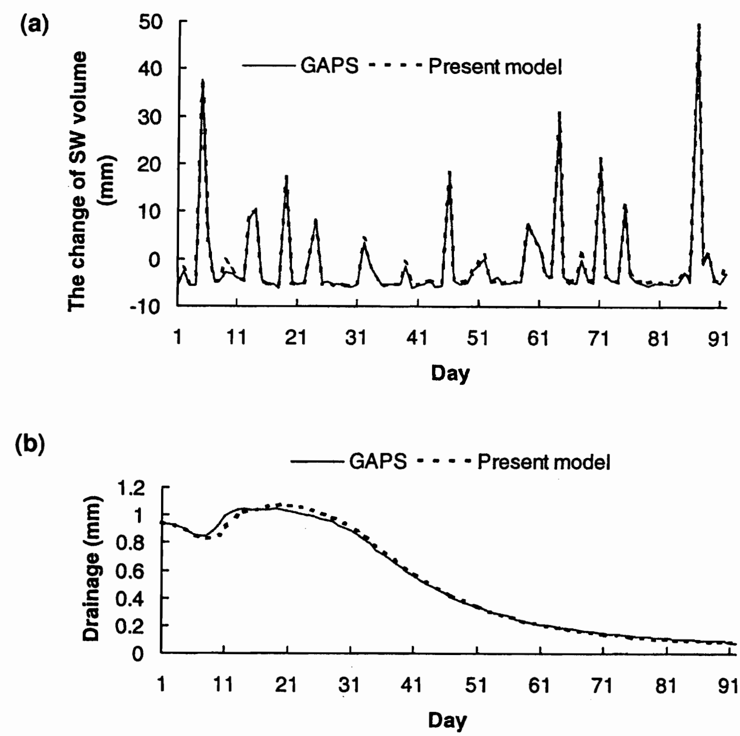

FIG. 1–Comparison of output from GAPS and the present model using meteorological data from 1983 for Armidale, NSW: (a) daily change of soil water storage; (b) daily drainage from the profile.

SIMULATION CONDITIONS

The basic simulation conditions are described here and the special conditions are indicated in each analysis in the Results and Discussion section. Three root patterns were used, each providing the same total root length per square metre of soil: (i) shallow even (SE) with constant root density to 0.625 m depth, (ii) deep even (DE) with constant root density down to 1.95 m, (iii) deep exponential (DX) with an exponentially declining root distribution

* Soil B value is the slope of the best fitted line relating soil matric water potential and volumetric soil water content on a log-log scale.

from a maximum at 0.05 m to zero at 1.95 m. The root length densities were from 0.3×10^4 m/m^3 to 1.0×10^4 m/m^3, which are typical of values previously reported (e.g., Carbon *et al.* 1980; Dell *et al.* 1983; Hulugalle & Willatt 1983; Eastham & Rose 1988). The soil was a uniform loam with saturated hydraulic conductivity value of 2.6×10^{-3} $kg/s/m^3$, air entry potential –1.0094 J/kg, soil B value 8.47, and saturated water content 0.52 m^3/m^3. Initial soil water contents were 0.35 m^3/m^3 down to 0.425 m depth, 0.30 m^3/m^3 from 0.425 to 0.9 m, and 0.25 m^3/m^3 below 0.9 m. These moisture contents were chosen to show most clearly the effects of rooting patterns on drainage, being just low enough that no significant drainage would occur until rainfall added more water to the profile. Meteorological conditions were such as to create a constant ETP of 5.46 mm/d (calculated from the Penman-Monteith equation under the conditions: canopy height = 1 m, leaf area index = 4, total radiation = 23 MJ/d, maximum temperature = 25°C, minimum temperature = 10°C, relative humidity = 70%). Two rainfall patterns were used: 50 mm falling every tenth day (approximately 10% less than ETP) and 60 mm every tenth day (approximately 10% greater than ETP).

RESULTS AND DISCUSSION

One of the main differences between trees and annual crops or grasses is root depth. Some trees in south-western Australia can have roots as deep as 40 m (Dell *et al.* 1983). Because of these deep root systems, trees have the ability to utilise soil water stored deep in the soil profile.

Root Patterns and Deep Drainage

Deep drainage under the three root patterns described under Simulation Conditions is indicated in Fig. 2. The root patterns all have the same root length per unit of land area. Deep drainage is affected by root distribution, being considerably greater for SE than for DE or DX because root patterns affect soil water distribution. If more of the roots occur at a shallow depth, such as in root pattern SE, then more water passes through the root zone and

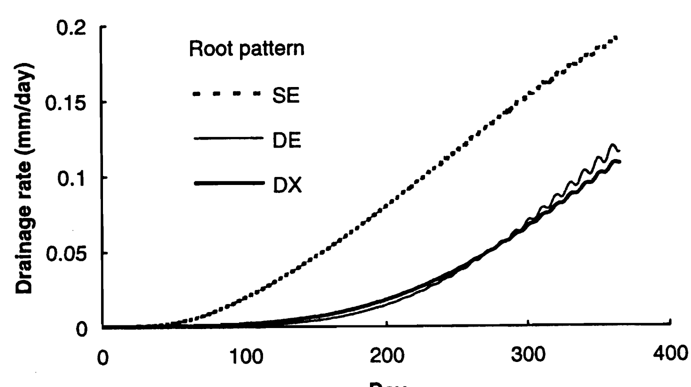

FIG. 2–The effect of root distribution pattern on simulated deep drainage over time when rainfall = 50 mm every tenth day (10% less than potential evapotranspiration). SE = shallow roots with uniform density, DE = deep roots with uniform density, and DX = deep roots with density declining exponentially with depth. Root length per unit of land surface is constant.

accumulates deeper in the soil profile, causing more deep drainage. Profile water content distributions at day 100 are shown in Fig. 3. Soil water contents in the upper soil profile are ranked SE<DX<DE and the order is reversed deep in the soil profile.

This effect on soil water distribution eventually affects the soil water balance. The water balance and soil water storage under the three root patterns after a simulation run of 1 year are shown in Table 1. Drainage under root pattern SE is more than twice that under root pattern DE or DX. Root water uptake under root pattern DX is slightly greater than that under root pattern SE or DE. This implies that root pattern DX is the most efficient for water uptake under these simulation conditions. The soil water storage change under root pattern SE is the least.

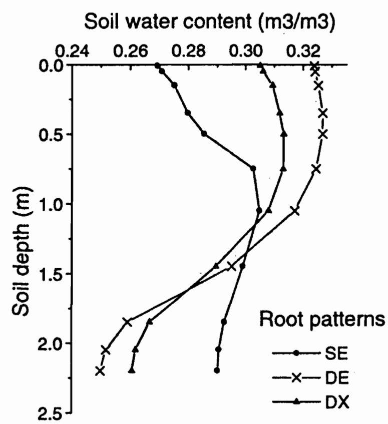

FIG. 3–The effect of root distribution on the soil water profile at day 100 for the simulations shown in Fig. 2.

TABLE 1–Components (mm) of the water balance after 365 simulation days for root patterns SE, DE, and DX. Rainfall = 50 mm every tenth day, and potential evapotranspiration = 5.46 mm/d.

Component	SE	DE	DX
Cumulative water uptake	1606	1595	1613
Cumulative evaporation from soil surface	113	113	113
Cumulative drainage	28	10	10
Increase in water stored in the profile	55	84	66
Final profile water storage	713	741	725
Water stored in active root zone (Ac)	199	664	642
Water stored in buffer zone (Bf)	433	0	0
Bypass water from root zone	513	77	82

The root distributions differ in the potential for further deep drainage if future rainfall is limited. This can be seen if the soil profile is divided into an active root zone (Ac), from the soil surface to just below root depth, and a buffer zone (Bf), from the active root zone to the boundary of deep drainage, which is taken here as the depth of the deepest roots, i.e., 1.95 m. Soil water stored in the active root zone may be used directly by roots, while that stored in the buffer zone will become deep drainage, assuming no root growth. Soil water stored in the active root zone for root pattern SE is 199 mm, which is much less than that under root pattern DE or DX. However, SE has a large amount of water in the buffer zone (433 mm). So, if the following period has little rainfall, the plants under root patterns DE or DX will use more stored soil water than under root pattern SE, and root pattern SE will allow the most deep drainage.

Effect of Root Patterns on Deep Drainage Depends on Accumulated Soil Water

Instantaneous deep drainage under different root patterns is related to soil water accumulation in the soil profile. To illustrate the change in deep drainage with soil water accumulation for the three root patterns, a constant rainfall pattern which slightly exceeds ETP (60 mm falling every tenth day) was imposed (Fig. 4). Initially, drainage was close to zero, being limited by insufficient water in the profile. However, as rainfall accumulated in the soil profile, drainage started to increase, with differences between the rooting patterns becoming evident. The final pulsed drainage pattern is a reflection of the repeating 10-day rainfall pattern. At this stage there was once again no difference in drainage (averaged over the 10-day cycle) between the different root patterns, because soil water contents were sufficiently high that plant uptake was no longer limited by the root distribution.

In the period following about day 50 and until around day 130, there were differences in deep drainage under the three root patterns. The influence of root distribution on deep drainage is evident when the soil is neither too dry (drainage is very small) nor too wet (drainage is limited by ETP not by roots).

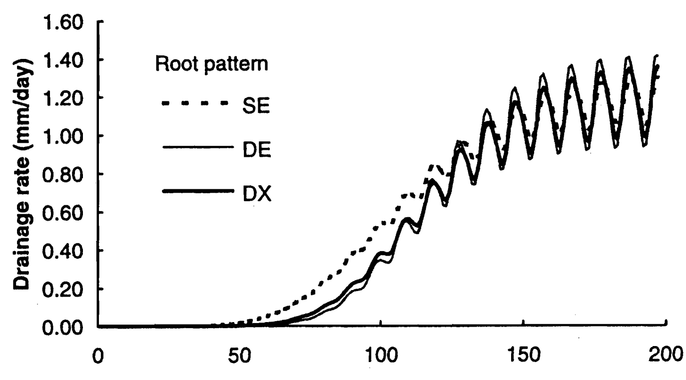

FIG. 4—The influence of root distribution on simulated drainage (rainfall = 60 mm every tenth day).

Effect of Root Distribution on Deep Drainage Under Real Weather Conditions

The aim of this section is to illustrate the effect of root distribution on deep drainage under real weather and more realistic root distributions. Historical rainfall and pan evaporation data for Armidale, NSW, from 1975 to 1977 were used. The daily rainfall totals are given in Fig. 5. Root depths and root densities were based on a realistic range of trees and grasses in this area (Fig. 6). It was assumed that all other characteristics of tree and grass such as evapotranspiration demand, total root length, root resistance per unit root length, and stomatal resistance response to leaf water potential stress, were the same. The effect of root patterns on deep drainage rate during the period is shown in Fig. 7, and was episodic in character. Differences in deep drainage between the grass and tree plots occurred mainly in wet periods. The tree root pattern allowed less deep drainage than the grass root pattern.

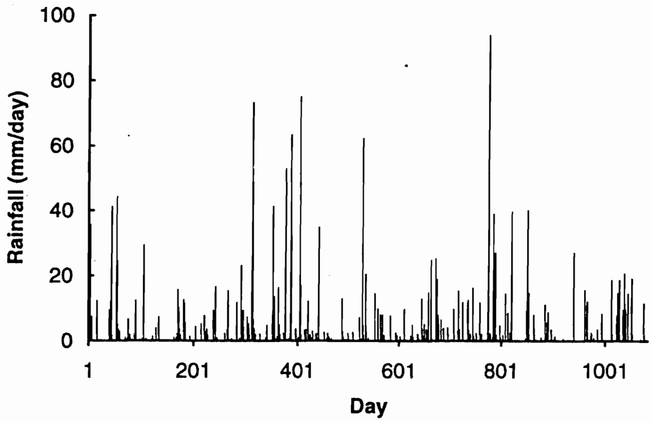

FIG. 5–Daily rainfall totals for Armidale, NSW, from 1 January 1975 (day 1) to 31 December 1977 (day 1096).

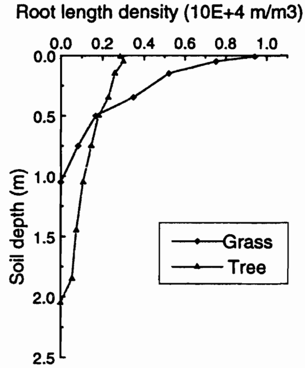

FIG. 6–Assumed root distribution for grass and trees used for simulation of deep drainage using Armidale meteorological data 1975–77.

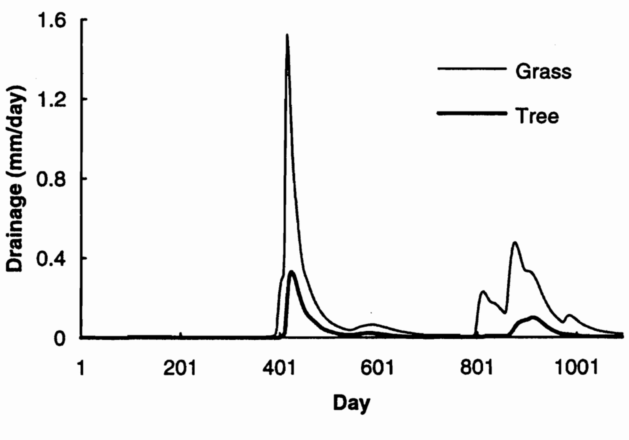

FIG. 7–Simulated deep drainage rate for trees and grass using Armidale meteorological data 1975–77.

Implication for Agroforestry Design

According to the analyses in previous sections, root distribution affects deep drainage. This naturally leads to the question as to whether there is an optimal root distribution. Optimal canopy structures have been studied for many years but optimal root distributions have seldom been explored. From the point of view of decreasing deep drainage, the more roots distributed deep in the soil profile, the more efficient the reduction in deep drainage. Trees are ideal for this purpose. However, the strategy for agricultural management is to maximise productivity and minimise the risk of environment degradation. Most productive annual crops or grasses have shallow root systems and so interplanting an appropriate proportion of trees in an agricultural area can cater to this strategy. Assuming the root water uptake abilities of two species are the same, the appropriate ratio of trees to grass or crops can be indicated by testing the effects of different percentages of deep roots on deep drainage. Deep drainage under different ratios of deep root to total root length after 365 simulation days, for a rainfall pattern of 50 mm every tenth day, is indicated in Fig. 8.

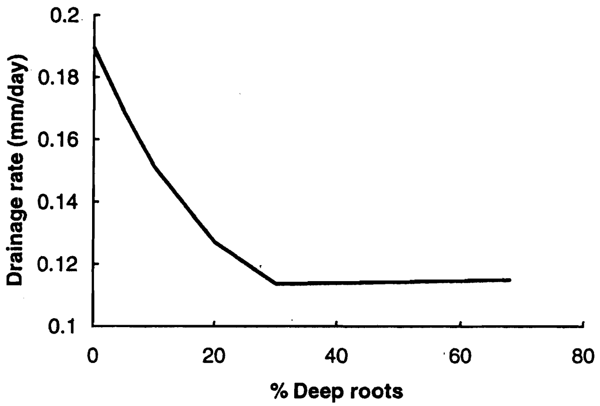

FIG. 8–The effect of increasing the proportion of deep roots (0.625–1.95 m depth) on deep drainage (rainfall = 50 mm every tenth day, 10% less than potential evapotranspiration).

Percentage of deep roots (on the X axis) indicates the ratio of roots distributed in the deep root zone—evenly distributed from soil depth of 0.63 m (the root depth of shallow-rooted species) to 1 m (the root depth of the deep-rooted species 1.95 m)—to total root length (26.7 $\times 10^4/m^2$). Deep drainage decreases rapidly as deep root percentage increases from 0 to 30%. However, further increase in the percentage of deep roots is of no benefit in decreasing deep drainage. This change in slope can be taken as the optimal root distribution. This means that, under these conditions of simulation, a substantial proportion of the roots can belong to economically productive shallow-rooted species, without increasing deep drainage.

To develop this concept further, assume that the root distribution in an agroforestry system is as shown in Fig. 9, where Z_1 is the root depth of a shallow-rooted species, and Z_2 is the root depth of a deep-rooted species. The optimal ratio of deep roots to total roots is obtained by simulation. Then, the proportion of tree roots to total roots can be calculated if the ratio of tree roots in the shallow zone to that in the deep zone is known.

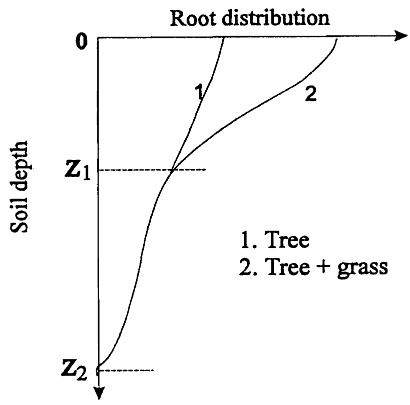

FIG. 9—Schematic description of the root distribution in an agroforestry system.

CONCLUSION

The model described here has been used to assess the influence of root distribution on deep drainage under a variety of environmental conditions. The numerical experiment found that root distribution affects soil water distribution and soil water balance. The effects of root distribution on deep drainage depend on soil water conditions. Root distribution has no effect on deep drainage under either too dry (drainage is limited by soil water content) or too wet (drainage is determined by ETP) soil water conditions. Simulation results also indicate that the role of trees in decreasing deep drainage in Armidale is during wet periods and drainage is generally episodic in character, only occurring during the wettest periods. To prevent excessive deep drainage, it may not be necessary to grow only deep-rooted species. Simulation can be used to suggest the optimum ratio of deep-rooted trees to shallow-rooted crops or grasses in an agroforestry system where the aim is to minimise deep drainage while maximising the percentage of productive shallow-rooted crops or grasses. In this way simulation can serve as a guide for the design of long-term field experiments.

None of the actual output behaviour of the model has been incorporated into its structure and yet its general behaviour is consistent with current understanding of water use in agriculture and forestry. The benefit of using a model such as the present one is that it provides a means of integrating many complex processes and understanding their interaction. Ultimately any model will be found to be deficient in some area, and the process of identifying these deficiencies can lead to a better understanding of water movement through the soil-plant-water system.

ACKNOWLEDGMENTS

We are grateful to Associate Professor D. MacLeod and Professor S. Riha for their valuable comments.

REFERENCES

BUTTLER, I.W.; RIHA, S.J. 1987: General purpose simulation model of water flow in the soil-plant-atmosphere continuum. *Applied Agricultural Research 2*: 230–4.

CAMPBELL, G.S. 1977: "An Introduction to Environmental Biophysics". Springer-Verlag, New York.

——1985: "Soil Physics with Basic". Elsevier, Amsterdam.

CARBON, B.A.; BARTLE, G.A.; MURRAY, A.M.; MacPHERSON, D.K. 1980: The distribution of root length, and the limits to flow of soil water to roots in a dry sclerophyll forest. *Forest Science 26(4)*: 656–64.

COWAN, I.R. 1965: Transport of water in the soil-plant-atmosphere system. *Journal of Applied Ecology 2*: 221–39.

DELL, B.; BARTLE, J.R.; TACEY, W.H. 1983: Root occupation and root channels of jarrah forest subsoils. *Australian Journal of Botany 31*: 615–27.

EASTHAM, J.; ROSE, C.W. 1988: Pasture evapotranspiration under varying tree planting density in an agroforestry experiment. *Agricultural Water Management 15*: 87–105.

GARDNER, W.R. 1960: Dynamic aspects of water availability to plants. *Soil Science 89*: 63–73.

HULUGALLE, N.R.; WILLATT, S.T. 1983: The role of soil resistance in determining water uptake by plant root systems. *Australian Journal of Soil Research 21*: 571–4.

MOLDRUP, P.; ROLSTON, D.E.; HANSEN, J. A.; YAMAGUCHI, T. 1992: A simple, mechanistic model for soil resistance to plant water uptake. *Soil Science 153(2)*: 87–93.

PECK, A.J.; WILLIAMSON, D.R. 1987: Effects of forest clearing on groundwater. *Journal of Hydrology 94*: 47–65.

PERSSON, G.; LINDROTH, A. 1994: Simulating evaporation from short-rotation forest: Variations within and between seasons. *Journal of Hydrology 156*: 21–45.

ROSS, P.J. 1990: Efficient numerical methods for infiltration using Richards' equation. *Water Resources Research 26(2)*: 279–90.

SCHOFIELD, N.J. 1992: Tree planting for dryland salinity control in Australia. *In* Prinsley, T.C. (Ed.) "The Role of Trees in Sustainable Agriculture". Kluwer Academic Publishers.

THORNLEY, J.H.M.; JOHNSON, I.R. 1990: "Plant and Crop Modelling—A Mathematical Approach to Plant and Crop Physiology". Oxford Science Publications.

van den HONERT, T.H. 1948: Water transport in plants as a catenary process. *Discussions of the Faraday Society 3*: 146.