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Simulation of Rooting Profile Using Soil Properties, Crop Characteristics, and Climatic Data

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Abstract

Observation and simulation of root development provides information on the soil resource utilization. Studying root growth with the support of a model helps envisage time-course changes in root development under varying environmental conditions. The quantitative root distribution with depth and over time is very essential for estimating the resource utilization. A modeling exercise was performed to characterize root development of five major crops in the semi-arid tropics (pigeonpea, cowpea, groundnut, sorghum, and pearl millet) using weather data, soil properties, and crop parameters. The model simulated the rooting profile for the investigated cereals and legumes adequately with the exception of pigeonpea. Pigeonpea showed a characteristic behavior of deep rooting nature on an Alfisol. However, the model was unable to simulate the crop's ability of penetrating and spreading its roots extensively into soil irrespective of a higher bulk density.

Introduction

Extensive researches have been carried out to characterize rooting pattern of each individual crop under defined environmental conditions. Quantitative data sets of parameters related to rooting patterns are necessary for the development of a sound model. In an excellent review of the development and growth of crop root systems, Klepper (1992) stated that although the individual parameters have been precisely tested under various soil conditions, for modeling purposes, generalizations that would apply to a range of soil types and conditions need to be developed and validated. Predictors of soil physical properties, such as strength, hydraulic conductivity, water retention, and soil chemical characteristics, should be available from soil databases if the soil type of the experimental site is identified (Jones 1983; Gupta and Allmaras 1987). In addition, an appropriate physically-based concept needs to be adopted to express the interactions between growing roots and soil (Dexter and Hewitt 1978; Richards and Greacen 1986). The appropriateness of

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these relationships determines the accuracy of the model for the prediction of root system development in field conditions.

Although root system morphology is genetically controlled, its architecture under field conditions is greatly influenced by carbon supply from the above-ground plant parts and soil physico-chemical properties. Another factor, which affects root system development and is especially important in relation to the soil resource utilization, is interaction of roots from neighboring crops of the same species in case of sole cropping and of different species in case of intercropping. To better predict root behavior by means of a model under a given set of conditions, all of the above variables should be carefully considered.

Our earlier studies (Gayatri Devi et al. 1996) on a short duration pigeonpea using the model presented by Jones et al. (1991) showed that the rooting profile for pigeonpea was satisfactorily simulated with a good correlation, with low intercepts, and with slopes tending to unity between observed and simulated values. However, the measured root length density for pigeonpea tended to be higher at the middle and lower depths than those simulated because of its ability to spread its fine long roots to a 20-60 cm depth. The thicker roots however were concentrated in the top layers, thus contributing to higher root weights at the surface. In contrast to pigeonpea, sorghum root studies showed that the root distribution was skewed towards the top layer with more roots at the surface contributing to higher root length densities and weights (Robertson et al. 1993). The ratio of root weight to length varied depending upon species or genotypes of crops and soil moisture status, especially at the surface layers of soils. A combined effect of these two factors on a length/weight ratio should be used to have more accurate prediction of the root distribution. The static soil factors, such as size distribution of soil particles and chemical composition, were found to be least restrictive. However, the model was shown to be very sensitive to even a small variation in bulk density as represented by the soil strength. Such variation is apparently a major constraint for root development.

The present study aims at developing the model for the simulation of the rooting profile of the individual component crops in an intercropping system under given soil conditions, such as soil type and dynamically changing soil variables like moisture, temperature, and aeration.

Five major crops were grown on an Alfisol in the semi-arid tropics (SAT) of India: a medium-duration pigeonpea (*Cajanus cajan* L. Millsp. cultivar ICP 1-6); cowpea (*Vigna sinensis* Endl. cultivar EC 82-7); groundnut (*Arachis hypogaea* L. cultivar ICGS-11); sorghum (*Sorghum bicolor* cultivar CSH-5); and pearl millet (*Pennisetum glaucum* L. R.Br. cultivar ICMV221). A monolith sampling method was used to measure root distribution at different soil depths in terms of root length and weight (for experimental details see Katayama et al. 1996). Root distribution was simulated using the model developed by Jones et al. (1991) and compared with observed data. Then, characterization of root system development among crops was then carried out based on model outputs, such as profile distribution, rooting depth, and root senescence.

Model selection

Crop models have been used to simulate growth processes. A model may also provide a powerful means of summarizing data and also a method for interpolation and cautious extrapolation (Thornley and Johnson 1990). Models are of varied types wherein simplicity, utility, plausibility, goodness of fit, and appropriateness to objectives are the properties to which a researcher attaches a certain weightage. He would then choose a model depending upon this weightage. A complex model may be the best only when all the input data are readily available. A simplified model may be preferred if it is credible and covers all the major relationships involved in the process. Various models that vary in complexity have been presented in the past to provide empirical distributions of root growth (Gerwitz and Page 1974) and daily increase in depth of rooting zone (Rosenthal et al. 1989). Some models account for the effects of temperature (Stone et al. 1983; Porter et al. 1986), water potential (Hoogenboom and Huck 1986), and other environmental effects (Jones et al. 1991). Whilst other models predict the morphology (Rose 1983), and architecture (Diggle 1988, 1996) of root systems.

The model used in this study has been described in detail by Gayatri Devi et al. (1996). It basically consists of two components. The first component is the simulation of soil moisture content and mean soil temperatures at the center of each layer, that are dynamic in nature and directly affect the root growth. The second component is to use these dynamic data sets for the operation of the root model (Jones et al. 1991) along with certain static parameters for the soil profile and genetic parameters of the plants. The root model applied in the present study, given the total dry matter allocated to the root on a daily basis, then attempts to simulate the daily rooting profile with depth. This is achieved based on simple mathematical equations to estimate the impact of weather variables and soil properties on root distribution. In the model, effects of both static and dynamic factors on root growth are expressed as stress factors, which range in value from 0 (no growth) to 1.0 (no stress). The model then simulates four processes that determine root distribution in the soil: (i) increasing depth of the rooting front; (ii) the length/weight ratio of new roots; (iii) root proliferation within soil layers; and (iv) senescence. The root model is expected to increase the sensitivity to several soil, crop, and environmental factors if incorporated into a whole-crop model.

Model inputs

Soil profile characteristics

Alfisols generally have low water-holding capacity and are characterized by lack of structural aggregation in the soil surface (El-Swaify et al. 1985). Murrum (hard-pan) layers in the sub-soil restrict root penetration for most annual crops. Soil samples of an Alfisol at IAC were collected at various depths and analyzed for physical and chemical properties by standard procedures. The soil profile data such as the lower limit of plant extractable water and drained upper limit of soil-water holding capacity required for input to the model were assembled by using the facility provided in Decision Support system for Agrotechnology transfer (DSSAT Ver. 2.1) software developed by International Benchmark Soils Network for Agrotechnology Transfer (IBSNAT).

Climatic data, soil moisture and temperature

Rainy season in the SAT is characterized by an erratic rainfall pattern which results in soil erosion, waterlogging, and aeration problems, and consequently affects root growth. The model therefore requires data on the amount of rainfall, and minimum and maximum temperatures as input on a daily basis. The model also requires daily changes in volumetric water content and soil temperature, which are output from Ritchie's multi-layered water balance sub-routine WATBAL and subroutine SOLT in CERES-Maize model (Jones and Kiniry 1986), respectively. The simulated volumetric water content clearly reflected the rainfall in all layers of the soil profile (data not shown). The regression between observed and simulated soil moisture values was high ($r^2 = 0.68 \sim 0.83^{**}$), with the slopes tending to unity and intercepts tending to zero.

Dry matter allocation to the root

The model requires total dry matter allocated to the root on a daily basis to simulate the rooting distribution along the soil profile for the various crops. Since a crop growth model has not yet been developed for pigeonpea, a logistic equation was used to fit the observed dry matter of roots to the time scale. Daily dry matter allocation to roots was then computed as the difference in the simulated root weight between two successive days.

The resulting daily total dry matter allocated to the roots of the cereals followed a similar trend, whereas variability among the legumes was observed (Fig. 1). Dry matter allocation to pigeonpea roots was low at the initial stage and then increased remarkably during the late vegetative period. In contrast, groundnut maintained a lower rate of dry matter allocation to roots throughout the growth period. Partitioning of dry matter to root and shoot has been discussed based on various theories. In the ROOTSIMU model (Hoogenboom and Huck 1986), the partitioning of carbohydrates between roots and shoot is determined by water status of the plant. Under water deficit conditions more biomass is distributed to roots. The shoot:root partitioning model is discussed extensively in Thornley and Johnson (1990) wherein substrate transport and its utilization for structural growth and shoot:root partitioning in response to variation in environment are addressed.

Crop characteristics of the root system

The length by weight ratios at the seedling stage and at the stage when the root is mature are required as input to the model. The other parameters are the maximum rooting depth, stage at which maximum rooting depth is attained, and that at which root senescence begins.

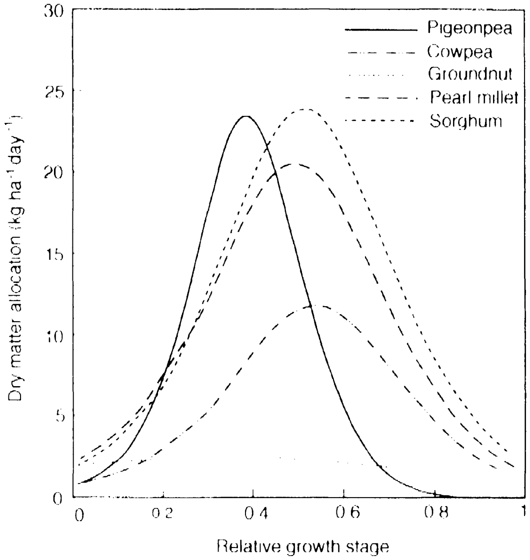

Fig. 1. Dry matter allocation to roots as obtained by the difference in root dry weight between two consecutive days. Data on root dry weight was fitted with a logistic equation. Relative growth stage: growth stage (0 - germination; 1 - physiological maturity) relative to an entire growth period (80 days for pearl millet and cowpea, 110 days for sorghum and groundnut, and 210 days for pigeonpea).

Model output

Root growth

Root growth in terms of root length density and root weight simulated by the model for two soil layers (0-10 and 20-30 cm depth) is shown in Figures 2 and 3. In cereals, root length density was higher in the surface layers and decreased with the soil depth. In legumes, the root length density was relatively lower (0.3 to 0.4 cm cm^{-3}) at the surface with an equivalent amount of root in the lower layers. For pigeonpea in particular, the root length density in the lower layers was underestimated by the model at the later growth stage (Fig. 3). This is because the root model is driven by the dry matter allocation to the roots provided as an input. Pigeonpea has a deep rooting system (Arihara et al. 1991). Root system of a dicotyledon, such as pigeonpea, consists of vertically-growing tap root and main laterals that enable the plants to explore nutrients in the deep soil layers. The higher-order laterals contribute to the increases in root surface area and consequently nutrient resource capturing ability in the layer. Elongation rate, diameter, and dry weight of dicot roots depend on plant vigor, shoot environment, and local soil conditions (Klepper 1992). Because of secondary growth, taproots and first-order laterals in the upper part of the soil profile are generally thick and heavy and their contribution to resource utilization may be lower due to the limited surface area than higher-order laterals. The present results show that the model is able to describe the basic differences in rooting profile between the cereals

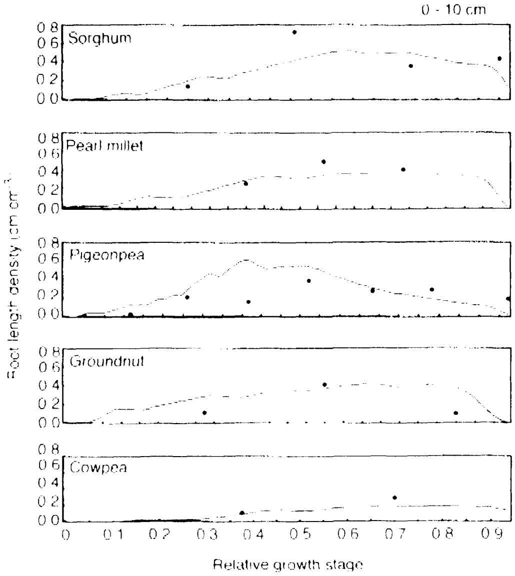

Fig. 2. Measured and simulated root length density at 0-10 cm for each crop.

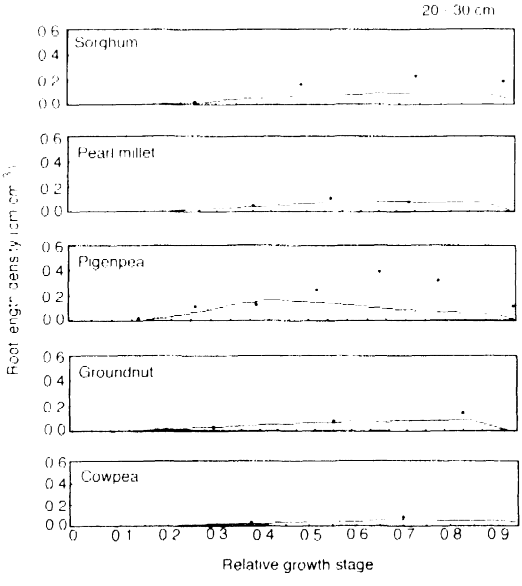

Fig. 3. Measured and simulated root length density at 20-30 cm for each crop.

and legumes, but further modification is required to achieve more realistic predictions, especially for pigeonpea.

Root distribution in terms of root length density of sorghum under well-watered conditions showed an exponential pattern with depth (Bloodworth et al. 1958; Ito et al. 1992; Robertson et al. 1993). It is often observed that root distribution with depth is largely altered depending on soil water content. As a result, the exponential distribution is not expressed in a number of instances when studies are conducted in soils with low moisture levels in the shallow layers (Blum and Arkin 1984) and pre-anthesis drought (Mayaki et al. 1976; Kaigama et al. 1977). The exponential fitting of root distribution along the soil profile is an empirical model which describes most root systems under non-limiting soil physical and chemical properties. However, the dynamic nature of root system calls for a model that takes into account the environmental factors which limit root system development under field conditions.

From the simulated data we observed that root length was reduced due to an increase in the bulk density in the layers around 10-30 cm, which was reflected in the measured values of root length for all crops except for pigeonpea, which recorded appreciable root length as compared with the simulated root length. This shows that pigeonpea is able to penetrate the hard-pan layer present in this particular field. Pigeonpea cultivars presently grown by the farmers originate from a woody perennial type, and are characterized by a rigid structure of root system with a firm taproot and main laterals. Although no comparative study has been carried out on the root penetrating ability of this crop, compared with other legumes, pigeonpea seems to have a higher ability to penetrate the hard soil.

Rooting depth

Rooting depth is another useful output from the model. When rooting depth is compared among the crops studied here using the growth stage relative to an entire growth period (refered to as relative growth stage), the rate of advance of the rooting front was the quickest in pigeonpea at the early growth stage, followed by cowpea (Fig. 4). The observations were made only up to 0.6 m, and all the crops reached the maximum observed depth by one-third of the entire growth duration. Pigeonpea and groundnut initially distributed more roots to the surface layer and then rapidly attained a deeper rooting depth, whereas the root development in cowpea was directed vertically downward right from the beginning. The cereals showed a slower rate of gain in the rooting depth as compared to the legumes. The measured rooting depth of cereals, such as millet and sorghum, has been shown by Monteith (1986) to increase linearly with time, similar to the simulation of the rooting depth by the root model.

The model could simulate the maximum rooting depth if the soil profile characteristics of the deeper layers are provided for. However, any discussion on the maximum rooting depth would be unrealistic without the support of observation. A number of literature exist on the maximum rooting depth of sorghum (Mayaki et al. 1976; Kaigama et al. 1977), of soybean (Kaspar et al. 1984) and factors affecting them. Hence, integration of all these factors in a model such as the one used in our study should give a better comparison of the rooting profiles of the various crops in an identical environment, provided the necessary input is available.

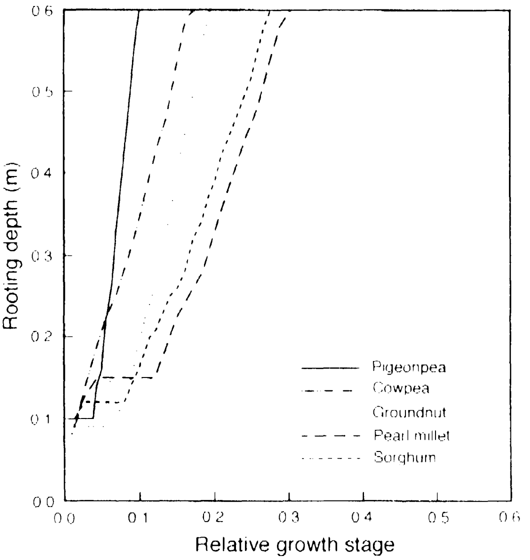

Fig. 4. Advance in rooting front (rooting depth) simulated by the model.

Root senescence

The daily loss of root weight expressed in kilograms per hectare per day (kg ha^{-1} day^{-1}) was highest in pigeonpea followed by pearl millet as shown in Figure 5. Sorghum showed the least amount of root senescence. The model simulates root loss equivalent to 1% of the dry weight in a layer per day and this increases by a factor of 2 when soil moisture is low and aeration poor. Robertson et al. (1993) assumed that root loss is 0.5% of existing root length per day in their model based on the CERES framework. The model ROOTSIMU is based on the concept that root senescence depends on soil temperature and the amount of reserve carbohydrate. Huck et al. (1987) have described the senescence of soybean roots as related to time and plant stress factors and have generated root decay functions.

Farmers in the semi-arid India include pigeonpea in crop rotation as they believe it helps sustain soil fertility. The contribution of pigeonpea in the maintenance of soil fertility is usually understood from its massive defoliation after flowering. The present study shows that pigeonpea has the highest amount of senescence among the crops considered. This suggests that supply of organic matter from the dead roots to soils may be another way to explain a role of pigeonpea in soil fertility maintenance. Barber (1979) observed that decaying corn root materials have a higher contribution to soil organic matter than shoots. This in turn would have a considerable effect on the soil properties and affect the growth of subsequent crops or other component crops in an intercrop.

Characterization of root growth based on model output

Considerable differences in the dry matter distribution to the roots (Fig. 1), and profile

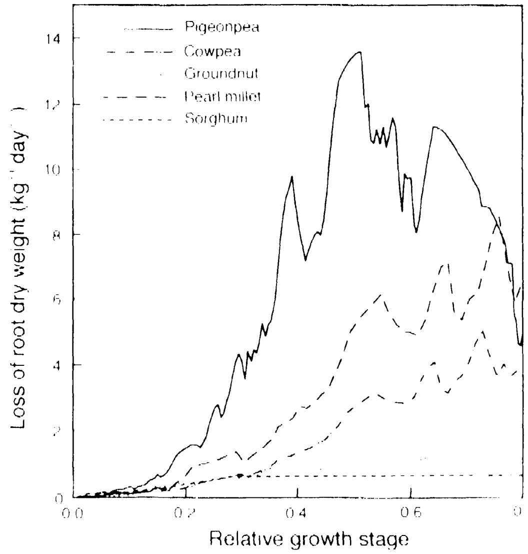

Fig. 5. Loss of root dry weight simulated by the model.

distribution of root length density with soil depth (Figs. 2 and 3) were observed between cereals and legumes. Beside the internal factors, the profile distribution of roots is also markedly modified by environmental factors such as soil temperature (Gregory 1986), fertility (Troughton 1980; Barber 1984), aeration (Grable 1966; Drew 1983), strength (Taylor and Gardner 1963; Taylor and Burnett 1964; Gerard et al. 1982), and toxic horizons (Adams and Moore 1983; Babalola and Lal 1977; Ritchey et al. 1982; Brenes and Pearson et al. 1973). Therefore, it is too presumptuous to draw a general view on the differences in rooting characteristics among the crops used before the model is run using a range of input related to the environmental variables. It should be noted that the following characterization is made based on data obtained from the particular environment and soil depth described earlier.

Conclusion

The rooting characteristics based on model output are summarized in Table 1. The root distribution in terms of root length density in the surface layer was higher in the cereals as compared with any of the legumes, whereas the legumes, especially pigeonpea and cowpea, reflected a higher measure in the central layers as compared with that of the surface layers. The root penetration of cowpea was faster than any of the other crops to a depth of 20 cm but pigeonpea reached a depth of 60 cm at a relatively earlier growth stage. Pigeonpea and groundnut reflected a considerable measure of root length density at 60 cm, meaning that they could reach deeper layers. The loss in root dry weight was earlier and greater in pigeonpea, followed by pearl millet and cowpea. Groundnut had low loss of root

Table 1. Root characterization to a soil depth of 60 cm based on model output.

	Sorghum	Pearl millet	Pigeonpea	Cowpea	Groundnut
Distribution					
0 - 10 cm	++	++	+	+	+
10 - 50 cm	+	+	++	++	++
Penetraion	+	+	+++	++	+
Rooting depth	+	++	+++	+	++
Senescence	+	++	+++	++	+

+, ++, and +++, magnitude where +++ > ++ > +

dry weight, and sorghum had a steady and very scanty loss.

We are still at the stage of figuring out the reasonable relationship in the interaction between roots and environment. To adequately predict root system development and resource utilization under intercropping situations, the following are essential. Firstly, the model has to be developed further to account for a rooting system as that of pigeonpea described earlier and secondly, more data on roots for multi-locational field experiments are required.

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