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EVALUATION OF SOME WATER EXTRACTION MODELS IN PREDICTING WATER UPTAKE OF PIGEONPEA

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Abstract. There is the need to have model(s) that best describe water uptake for pigeonpea. Three water extraction models published in the literature and one suggested by this author were examined for two pigeonpea genotypes (ICPL 87 and ICP 1-6) grown under field conditions on an Alfisol. The accuracy of the models was evaluated by comparing the water extraction rate using the models with the traditional water flow equation in soil including a sink/source term. Prediction of water extraction by the author's model agreed very well with those from the traditional water flow equation in soils ($r = 0.999$). Gardner and Hillel *et al.* models performed moderately well in terms of their predictive capabilities. Other factors limiting the predictive capabilities of the models and suggestions for improving them were also discussed.

Keywords: water extraction model, pigeonpea

INTRODUCTION

Water is essential for cell division, photosynthesis and transpiration in plant. Most crop growth and development processes therefore depend on water. Through its effects on water content, water extraction rate influences the infiltration rate and therefore run off and soil profile water storage which are major constraints to crops production on Alfisols. Understanding the processes and mechanisms involved in water extraction by roots is a prerequisite to: (i) modeling the water budget of root zone which often forms a component of crop models and (ii) the development of sound and sustainable crop management systems in the tropics.

Very often, crops are incapable of extracting water that may be present at greater soil depth even during prolonged drought [8]. However, the roots of pigeonpea, which is a protein source of food for most of the inhabitants in developing countries, is able to penetrate deeper horizons of the soil profile. Its slow growth at the begining of the rainy season and rapid growth later in the season make pigeonpea particulary suitable for intercropping with either short duration crops such as cowpeas or crops that have initial rapid growth such as sorghum and maize. Physically based submodels that describe the water of pigeonpea would supplement a whole crop model and would facilitate the extrapolation of research results from one location to similar agroecological regions.

Generally, there are two approaches to modeling water extraction by roots, viz.: a macroscopic analysis that integrates properties of the entire rooting zone, and a microscopic method that is based on the analysis of a single root. The latter approach is not widely accepted because it is often the performance of the plant community as a whole rather than the individual plants that is important. In the macroscopic approach, water extraction by roots is formulated by an addition of a sink term, S (M/day) to the differential equation describing the 1 - dimentional flow of water in soil. The traditional model then is of the form:

$$(\partial\theta/\partial t)\, dz = \partial/\partial z\, (K_\theta\, \partial H/\partial z) - S(z, t) \quad (1)$$

where θ is the volumetric water content (cm^3/cm^3), t is time in days (d), H is the total hydraulic head (cm), K is the hydraulic conductivity (cm/day) and z is depth (cm).

Different models of water transport through the soil-plant-atmosphere continuum including those examined in this study have been reviewed very well by Tinker [14], Rowse *et al.* [13] and Moltz [9]. Two basic inferences from the reviews are: (i) the existing models of water transport in plants are oversimplified and therefore of limited use in a truly predictive sense, and (ii) the appropriate model for a particular application must be selected carefully.

In this study, the extraction models (Table 1) of Gardner [4], Hillel *et al.* [7], Herkelrath *et al.* [5] and author's modified function of Passioura [12] were evaluated with experimental measurement in order to ascertain those that best describe water extraction of pigeonpea on an Alfisol (Table 2). The materials and methods for generating the data used in this paper are available in previous paper [11].

Table 1. Water extraction models examined in the study

Model	Model equation	Equation no.	Author(s)
M-I	$S = Bh\,(\psi_r - \psi_s - Z)KL$	(2)*	Gardner [4]
M-II	$S = (Hs_i - Hc)/(Rs_i + Rr_z)$	(6)	Hillel *et al.* [7]
M-III	$S = \theta/\theta s\; eL(Hrs - Hp)\; h$	(8)	Helkelrath *et al.* [5]
M-IV$_{ovf}$	$S = \int_{z_1}^{z_2} (-\theta i/T) \exp[-(t-ti)/T]\, dz$	(12)	Author
M-IV$_{vf}$	$S= \int_{z_1}^{z_2} (-\theta i/T) \exp[-(t-ti)/T]\, dz + K_\theta\, (\partial H/\partial z)\, z_2 - K_\theta\, (\partial H/\partial z)\, z_1$		Author
M-O$_{ovf}$	$S = \int_{z_1}^{z_2} (\partial\theta/\partial t) dz$	(14)	Traditional function
M-O$_{vf}$	$S = \int_{z_1}^{z_2} (\partial\theta/\partial t) dz + K_\theta\, (\partial H/\partial z)\, z_2 - K_\theta\, (\partial H/\partial z)\, z_1$	(13)	Traditional function

* Refers to equation number in the test for the definition of the equation parameters.

Table 2. The physical and hydrological properties of the soil horizons

Soil layers (cm)	Saturated water content ($cm^3\, cm^{-3}$)	Air-dry soil moisture content ($cm^3\, cm^{-3}$)	Saturated hydraulic conductivity (cm/day)	Bulk density (G/cc)	Gravel (%)	Remarks
0-22.5	0.323	0.016	30.95	1.68	5.65	Sandy loam with very low gravel
22.3-37.5	0.374	0.089	20.18	1.65	4.90	Sandy clay with very low gravel
37.7-52.5	0.392	0.101	40.61	1.56	6.40	Clay with very low gravel
52.5-75.0	0.416	0.112	113.98	1.54	7.21	Clay with very low gravel
75.0-105.0	0.364	0.099	21.08	1.63	10.09	Clay, gravelly and stony
105.0-135.0	0.360	0.079	23.07	1.15	37.33	Clay loam, highly gravelly/stony
135.0-165.0	0.406	0.075	31.06	1.13	35.88	Sandy clay loam with moderate gravel
165.0-195.0	0.408	0.085	22.94	1.35	22.97	Sandy clay loam with moderate gravel

THE MODELS

The extraction model of Gardner [4] (M-1)

The model is based on the assumption that the rate of water movement from soil into plant root is proportional to the difference between the free energy of water in the plant root and that in the surrounding soil. The osmotic component of the total suction and the impedance to water movement in the root were considered negligible in the derivation of (M-1) which is usually re-written as:

$$S - Bh\,(\psi_r - \psi_s - Z)KL \qquad (2)$$

where S is rate of water extraction by roots per unit cross section of a layer of soil thickness h, ψ_r - suction in the roots at the crown (cm), ψ_s - soil matric suction (cm), Z - vertical distance from the soil surface to the middle of the layer under consideration (cm), K - unsaturated hydraulic conductivity of the soil (cm/day) measured according to Tinker [14] and Hillel *et al.* [6], L - root length density (cm of root/cc of soil), B - constant.

In this study, parameters h, ψ_s, Z, K and L were field measured values as described in the previous paper [11]. The parameters B and ψ_r were estimated by solving two equations simultaneously which were formed using the following relationship at two soil depths using multiple data sets and average parameter values thus:

$$S = Bh(\psi_r - \psi_s^*)\,K^* \qquad (3)$$

where ψ_s^* is the integrated soil suction defined as:

$$\psi_s^* = [\Sigma K_i L_i (\psi_{s_i} + Z_i)]/\Sigma K_i L_i \qquad (4)$$

and

$$K^* = \Sigma K_i L_i\,. \qquad (5)$$

The parameter ψ_r was taken to be constant throughout the rooting zone for a particular day. Equation (4) was developed based on the assumption that extraction of water by the roots would be such that the total soil moisture status would at any time remain constant throughout the root zone. Thus a given average soil matric suction (ψ_s^*) would be representative of the entire root zone [15]. In solving Eq.(2) however, different ψ_s was used for each layer.

The extraction model of Hillel *et al.* [7] (M-II)

Hillel *et al.* [7] assumed that the flow rate of water to the roots from any particular soil layer i is equal to the ratio of the difference between the total soil water potential in that layer (Hs_i) and the potential at the root crown (Hc) to the total hydraulic resistance. The total hydraulic resistance was taken as the sum of the soil hydraulic resistance (Rs_i) to flow of water towards the roots in the soil, and the resistance of roots (Rr_i) to water flow. The model is thus:

$$S = (Hs_i - Hc)/(Rs_i + Rr_i)\,. \qquad (6)$$

Hillel *et al.* [7] further assumed in deriving M-II that water potential of the roots in the entire rooting zone is equal. He did not include any above surface plant function.

In parametirizing the model in this study, Hs_i was field measured soil water potential (cm). Rs_i was taken as $1/BKLp$ where B is a constant taken as 1, K is the soil hydraulic conductivity and Lp is the patrial root length density defined as the ratio of the product of root length in layer and root profile depth to the volume of soil in the rooting profile depth. Both K and Lp were from field measured data described previously.

Rr_i was taken as $RTRSU\,(Depthi{+}1)/Lp$ where $RTRSU{=}1.05\,Z_i$ where Z_i is the distance from the soil surface to the midpoint of the compartment, $Depth_i$ - thickness of the layer (cm), Lp - as described for Rs_i.

Hc in Eq.(6) was determined from the relationship:

$$Hc = [\Sigma(Hs)_i/((Rr)_i + (Rs)_i) - Q]\;/$$

$$\Sigma'/((Rr)_i + (Rs)_i) \qquad (7)$$

where Q (the transpiration rate) was calculated from $\Sigma h\, \partial\theta/\partial t$ in the different soil layers in the root zone.

The extraction model of Herkelrath *et al.* [5] (M-III)

It is a root - contact model which assumes that as the soil dries, the surface area of roots in contact with soil decreases, resulting in an increase in root membrane resistance. The effective conductivity of a root segment is thus assumed to be proportional to the wetted fraction ($\theta/\theta s$) of the surface area of that segment, where θ is a bulk soil water content and θs is saturated soil water content.

In deriving M-III, the potential drop within the plant is neglected so that the water potential at the root surface, Hrs (cm) and that inside root, Hr (cm) are respectively approximated by using field measure soil matric potential between plant stands within a raw (Tensiometric), and average water potential of plant stems as close to the ground as possible (pressure chamber), [2]. The model equation is as written below:

$$S = \theta/\theta s\; eL\, (Hrs - Hp)\, h \tag{8}$$

where L is the root length density (cm of root/cc of soil), h is the thickness of the soil layer, e - root permeability per unit length of root (cm/day) which is estimated from: $e = -\frac{\partial\theta}{\partial t}\frac{\theta s}{\theta}\frac{1}{Hrs-Hp}\frac{1}{L_i}$ using multiple data sets and average the parameter values for a day before the intended day of extraction rate prediction and for each layer. In this model, the major resistance to water extraction is attributed to be in the root and not in the soil. It also assumes that there is no longitudinal resistance to water flow within the root.

Author's water extraction model (M-IV)

This is the modified version of water extraction equation of Passioura [11]. He suggested that:

$$\theta = \theta a \exp(-DLT) \tag{9}$$

where θ is total extractable water at time equal zero, L is the rooting length density (cm) and D is a constant regarded as a measure of the diffusion properties of the soil over there velantrange of water content (cm^2/day).

Passioura [11] and Monteith [10] defined the parameters of Eq.(9) in different ways, thereby introducing some ambiguties. Passioura [11] defined θ as the water content in excess of θ at moisture potential H = -15 bars, $\theta a = \theta$ at $t = 0$ and t - the elapsed time.

On the other hand, Monteith [10] replaced DL by $1/T$ and defined θ as the water content inexcess of θ at the lowest limit with the ambiguities associated with the definitions of field capacity, wilting point, upper limit, lower limit and available water content in bulk soil and at the root surface. Both of them assumed that for all values of $t > ti_z$, the root length density has a fixed value and θ_z decreases according to Eq.(9). Even though this assumption is plausible, it is possible that once the root front has penetrated deeper, L would not remain fixed due to root proliferation, extension or mortality.

In this study, the parameter of Eq.(9) is redefined to impart clarity and make it useful for field conditions. Thus Eq.(9) is rewritten and redefined as:

$$\theta_{z,t} = \theta i_z \exp(-t/T) \tag{10}$$

where $\theta_{z,t}$ is water content at the end of water extraction time t in days after sowing, θi_z - total extractable water at the begining of extraction at depth z and at time ti in days after sowing. The difference (t-ti) should be short enough (about 5 days) to permit the validity of the assumption that $Dz\, Lz = 1/T$ is constant.

The rate of extraction of water at z and time t is then given by:

$$-\,\partial\theta/\partial t = (\theta i/T)\exp(-t/T)\,. \tag{11}$$

Integration of Eq.(11) with respect to z gives:

$$\int_{z_1}^{z_2} (\partial\theta/\partial t)\, dz = \int_{z_1}^{z_2} (\theta_i/T) \exp[-(t-ti)/T]dz = S\,. \tag{12}$$

where ti is the initial time in days after sowing, T is a time constant assumed inversely proportional to root density. T is governed by soil environment, simultaneous movement of the water towards roots by diffusion and of roots towards water by extension and light interception. It has the unit of resistance to water extraction by roots.

The parameter T is estimated by regressing: $\ln\theta$ on $(t-ti)$ in $\ln(\theta) = \ln(\theta i_z) - (t-ti)/T$ to obtain the slope which is equal to time constant $1/T$ and intercept equal $\ln(\theta i_z)$. In this study this was done for each layer and each extraction period.

In deriving this model, rainfall (p) and evaporation (Ea) could be accounted for by adding ($P-Ea$) to both sides of Eq.(12) even though it was examined for rainless periods and no irrigation. Equation (12) is without the storage term (M-IV$_{ovf}$) while the one with the vertical flux adds on to it the storage term $[K_\theta\, \partial H/\partial z_{z_i} - K_\theta\, \partial H/\partial z_{z_{i-1}}]$ indicated by M-IV$_{vf}$.

Measurement of water extraction by roots using traditional dimensional equation (M-O)

As indicated in the part describing model M-1, water extraction from any layer of soil is the rate of change of water content and the net capillary flux between the bottom and top of that layer. Thus, upon integration and rearrangement, the water extraction rate S (cm/day) is:

$$S_{vf} = \int_{z_1}^{z_2} (\partial\theta/\partial t)dz + K_\theta\,(\partial H/\partial z)/z_2 - K_\theta\,(\partial H/\partial z)/z_1 \qquad (13)$$

when vertical flux is considered (M-O$_{vf}$), and:

$$S_{ovf} = \int_{z_1}^{z_2} (\partial\theta/\partial t)\,dz \qquad (14)$$

when vertical flux is neglected (M-O$_{ovf}$).

In this study measured parameters in Eqs (13) and (14) were used to determine water extraction rates by M-O$_{vf}$ and M-O$_{ovf}$ which were then compared with S from the extraction function of M-I, M-II, M-III and M-IV.

Note

Mathematical integrations were carried out using PCSMP on IBM - PC's.

RESULTS AND DISCUSSION

Table 3 presents the regression parameters obtained by regressing the models' water extraction predictions on those obtained from the standard water extraction functions (M-O$_{ovf}$ and M-O$_{vf}$). The performances of the models were evaluated based on the concept of perfect fit between standard and the evaluated models where a slope (b)=1, intercept (a)=0 and a correlation coefficient (r)=1 are expected.

Model M-I

Analysis showed that the S values from M-I agreed well with the traditional function at the early growth stages of the 2 genotypes, especially when the vertical flux term was neglected (Table 3). A comparison of S calculated using M-I with the standard (Fig. 1) indicates that the water extraction patterns for the 2 cultivars (M-1a in Fig. 1) differed markedly from the standard (M-O$_{ovf}$ in Fig. 1) when data from the 5 sampling periods (51, 68, 83, 104, and 125 DAS) were used in the regression analysis. However, removing the data of 104 and 125 DAS from the analysis, the agreement was better (Table 3 and M-1b in Fig. 1). The results show that the suggestion by Gardner and Ehlig [3] that the resistance offered by roots was negligible compared to that in the soil might not be true in this case. Their findings were based on experiments with plants grown in shallow containers (less than 40 cm deep) containing both large and small diameter roots. In this present experiment, the roots in the deeper soil layer were mostly smaller in diameter compared to those in the upper layer. These smaller roots may offer considerable resistance to water flow, because roots in the deeper part of the profile are mainly responsible for water extraction as the

Table 3. Regression parameters of water extraction models with the traditional water extraction functions in pigeonpea cultivars ICPL 87 and ICP 1-6

Model author	Model number		Intercept (a)	Slope (b)	Correlation coefficient (r)	+Vertical - Flux (vf)	Genotype
Gardner	M - I		2.218	3.436	0.1585	- vf	ICPL 87
		(+)	0.034	0.634	0.9032	- vf	ICP 1-6
		(+)	0.066	0.679	0.9889	- vf	ICPL 87*
		(+)	0.122	0.461	0.9826	- vf	ICP 1-6*
			2.170	3.435	0.1331	+ vf	ICPL 87
			0.135	0.345	0.7898	+ vf	ICP 1-6
Hillel *et al.*	M - II	(+)	0.018	0.866	0.9968	- vf	ICPL 87
		(+)	0.034	0.685	0.9903	- vf	ICP 1-6
			0.082	0.601	0.5812	+ vf	ICPL 87
			0.143	0.390	0.9047	+ vf	ICP 1-6
Herkelrath *et al.*	M - III		0.121	0.634	0.7539	- vf	ICPL 87
			0.039	0.469	0.9618	- vf	ICP 1-6
			0.120	0.606	0.6050	+ vf	ICPL 87
			0.113	0.264	0.8695	+ vf	ICP 1-6
Author	M - IV	(+)	0.001	1.015	0.9999	- vf	ICPL 87
•		(+)	0.003	1.017	0.9990	- vf	ICP 1-6
	M - IV	(+)	0.0002	1.009	0.0\9998	+ vf	ICPL 87
		(+)	0.004	1.100	0.998	+ vf	ICP 1-6

* Only early three sampling periods considered, neglecting the last two later growth sampling periods; (+) promising models.

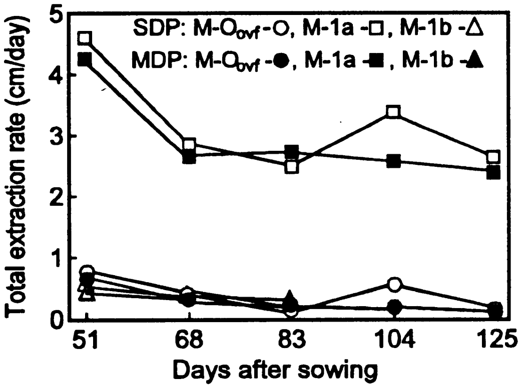

Fig. 1. Comparison of M - I with no vertical flux standard equation (M - O_{ovf}) for predicting water extraction by roots of SDP and MDP as a function of days after sowing.

soil dries out from the surface as a result of the atmospheric demands. The other reason could be the fact that in the later growth stages of pigeonpea, the transpiration demand may be very low due to defolation.

This model neglects vertical flux and assumes that single values of B and ψ could represent the different soil layers in spite of the variations in root size, soil physical and chemical characteristics. If B in M-I is truly a measure of the density of the root system, then a single value would not adequately represent B. Similarly, if the assumption of continuous decrease in potential energy of the soil-plant-atmosphere continuum from the rhizosphere until the water reaches the leaf surface where it evarporates holds, then a single ψr value can not represent the suction in the root in different soil layers. M-I could be useful for only shallow rooted crops or at the early growth stages of pigeonpea.

Model M-II

Model M-II agrees better with the standard function for water extraction rate in SDP than for MDP when vertical flux was neglected in the standard function for the regression analysis (Fig. 2 and Table 3). The results show that agreement between model and the standard function depends on the cultivar and the vertical flux consideration in the computation of the water extraction rates (Table 3).

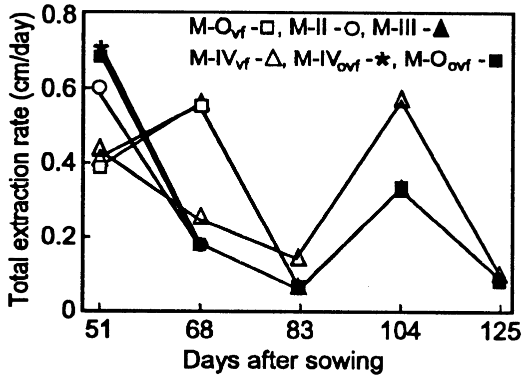

Fig. 2. Comparison of total root water extraction rates from standard equations with ($M - O_{vf}$) and without ($M - O_{ovf}$) vertical flux and some promising models in short duration pigeonpea (SDP).

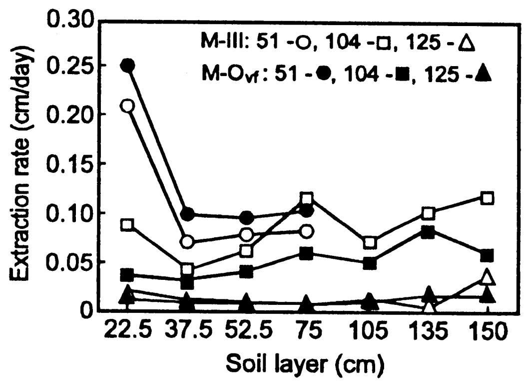

Fig. 3. Comparison of the extraction rates from M - III with the standard equation ($M - O_{vf}$) as a function of soil layer at 51, 104 and 125 days after sowing the short duration pigeonpea (SDP).

As compared to SDP, the roots of MDP are less exploitative of soil water. The vertical flux in MDP is then quite considerable. The SDP which extracts more moisture from the soil profile leaves the soil drier than in the case of MDP. M-II then agrees better with the standard when vertical flux is neglected for SDP than for MDP and vice versa when vertical flux is considered.

The predictions from the M-II are generally good. This could be due to the fact that, M-II is more of curve fitting being circular in the estimation of Q, the transpirational rate used to parametirize the model from $\Sigma h\ \partial\theta/\partial t$.

Model-III

Irrespective of the cultivar, M-III correlates better with the standard function without the vertical flux component (Table 3). However, this model merely describes the trends in water extraction by roots in the different layers of the soil profile. In other words, not very predictive in the absolute term (Figs 2 and 3). The model could only pick the actual extraction rate during periods of relative water stress in the soil profile as experienced in day 68, 83 and 125 for SDP (Fig. 2) corresponding to its active vegetative, budding and podding growth stages, respectively. The perfect description of the water extraction rate trend by M-III is due to the method used to estimate the root permeability which forces the theory to fit the experiment at one point on each curve. This does not lead however to the understanding of the processes. Secondly, the permeability estimated a day prior to predicting the water extraction rate by root may not apply to predicting the water extraction rate for that day.

Model M-IV

The agreement between the *S* values from M-IV and M-O is excellent (Table 3 and Fig. 2). The *S* values from $M\text{-}IV_{ovf}$ agreed very well with $M\text{-}O_{ovf}$ in Eq.(14) where the vertical flux term is neglected. Even though M-IV predicted the *S* values excellently, it involves rigorous integration procedures.

The performance of model M-IV providing the best fit to the traditional equation may be due to the similarity in their functional form (Eqs 12-14). The *T* parameter in model M-IV (Eq.12) which was determined by regression analysis against the field data also contributed to the perfect agreement (r=0.999, see Table 3) between model M-IV and the measured data. Further work is required to parametirize *T* in a more physical term to make M-IV describe the physical processes involved in the system.

CONCLUSIONS

The two versions of M - IV predict water extraction of the 2 genotypes of pigeonpea accurately. Models M - I and M - II give a fairly good prediction of water extraction, particularly of

SDP when the vertical flux term is considered to be negligible in (13), thus permiting the use of (14) for comparision. M - III is good under relatively dry conditions and at certain growth stages of the crop.

Parameter estimation for some models is highly dependent on several difficult field measurements (K_θ, root density, etc), thus the performance of the models may to some extent be attributed to sampling rather than the functional form of the models. Therefore, model M - IV provided the best fit because of the method used in the evaluation and may not be the best representation of the system.

These models my be improved by incorporating a vertical flux term. It should be noted that (13) and (14) describe a one-dimensional flow phenomenon and do not include lateral movement of water in the soil. This and the assumption of the negligible osmostic potential may account for some of the discrepancies between S from the models and S values calculated using (13) and (14). The root hydraulic resistance which is thought to be neglibible in other crops may be a significant parameter in pigeonpea when one considers its inability to exploit all the stored water content in the soil profile in spite of its deep rooting system. Most of the models evaluated lack physical description of the processes involved to make them useful in whole crop modeling. There is the need to re-parametirize them to make the excercises and the concept useful to the irrigation managers, soil physics people, ecologists and those involved in modeling soil - plant - atmosphere systems.

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