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Simulation of the dry matter production and seed yield of common beans under varying soil water and salinity conditions

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Abstract

We present a model that simulates the effects of water and salinity stress on the growth of beans. The model derives a combined soil water/salinity stress factor from the total water potential (combination of the matric and the osmotic potentials) and uses this stress factor as a growth limiter in a growth model. The model was tested on data obtained from two greenhouse trials of beans (*Phaseolus vulgaris*) grown under a range of soil water and salinity conditions. The simulated dry weight of the bean generally followed those observed. In the first trial, the comparison between simulated and observed total dry weight and seed yield gave R^2 values of 0.97 and 0.92, respectively. Comparison of the simulated to the observed dry weight for the second trial gave R^2 values of 0.85 and 0.89, respectively. These indicate a good performance of the model in general. The principle of deriving a combined water/salinity stress from the matric and osmotic potentials is simple and can be included as a simple routine in many existing crop models without much difficulty. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Beans; Crop growth simulation; Soil salinity; Soil water stress

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1. Introduction

Crop models are used as tools for enhancing agricultural research through the identification of gaps in knowledge (Uehara, 1989) as well as by providing support for decision making in agricultural planning (IBSNAT, 1989). Despite the increasing availability of models worldwide, their use in both agricultural research and for decision making in many parts of the tropics is still very limited. The limited scale of crop model development and application in this region can be attributed to several constraints such as the lack of comprehensive database (e.g. climatic and soil data) in readily electronic-readable forms as required by models. But more importantly, most of the commonly available functional models do not include routines necessary for the simulation of the effects on plant growth of some important features peculiar to the tropical and sub-tropical environment, such as soil salinity and acidity.

The constraint of soil salinity on crop growth is the concern of this study because considerable portions of the semi-arid soils in the West African tropics are salt affected. Soil salinity may result from the nearness of the semi-arid sites to the sea or due to the rise of saline groundwater into the root zone and concentrating there when evaporation becomes excessive. Soil salinity may also arise in irrigation lands where leaching is inadequate, leading to the accumulation of salts within the root zone.

Crop models that are appropriate for application in the saline, semi-arid regions must consider simultaneously the effects of both water stress and salinity on crop growth. It is known that water stress results in growth reduction (Stewart et al., 1977) apparently due to the closure of stomata leading to the reduction in CO_2 intake by the plant. Based on this, the effect of water stress on plant growth may be expressed in terms of the soil water availability, so that a stress factor can be formulated in terms of the matric potential of soil water (Feddes et al., 1978). In the case of soil salinity, the adverse effects on plant growth may be attributed to two main factors. Firstly, there may be a direct toxicity of the excess of specific ions leading to nutritional disorders (Bressler et al., 1982). Secondly, there may be an indirect effect through the reduction in the osmotic potential of the soil water that leads to a decline in plant water uptake (Mass and Hoffman, 1977). Previous attempts to quantify the effect of salinity on plant growth have used production functions that relate the decline in crop yield to the average root zone salinity. For example, van Genuchten (1983) proposed a number of empirical functions that express the relative yield (actual to potential yield) of some vegetables (e.g. tomatoes, pepper) in terms of the root zone salinity. Since such functions only consider the final yield of the plant, i.e. having a time scale of a whole crop cycle, they are inappropriate for the day-to-day management of soil water and salinity.

What we desire is the derivation of a process-related soil water and salinity stress factor that can be applied dynamically throughout the growth cycle. If the direct toxicity effects of the salts on plant growth are negligible, then, as indicated above, salinity stress may be expressed in terms of the solute or osmotic potential of the soil water. Basic soil physics theory indicates that water potentials are additive. Hence, by expressing water and salinity stress in terms of the matric and osmotic potentials, respectively, it may be feasible to formulate a combined water/salinity stress factor from the total soil water potential.

The aims of this study are, therefore, to (i) to formulate a simple combined water/salinity stress index from the daily variations in the soil water content and salt concentration, and (ii) use this stress factor in a crop model to simulate the growth of beans (*Phaseolus vulgaris*) under varying soil water and salinity conditions.

2. Theory

2.1. Derivation of a combined water/salinity stress factor

Many workers (e.g. Feddes et al., 1978) have shown that in the absence of salts, a water stress factor, α, which can be used as a growth modifier, can be formulated as a function of the matric potential, Ψ_{m}, as

$$\alpha(\Psi_{\mathrm{m}}) = 1, \quad \Psi_{\mathrm{m}} > \Psi_{\mathrm{c}} \tag{1a}$$

$$\alpha(\Psi_{\mathrm{m}}) = \frac{\Psi_{\mathrm{m}} - \Psi_{\mathrm{l}}}{\Psi_{\mathrm{c}} - \Psi_{\mathrm{l}}}, \quad \Psi_{\mathrm{l}} < \Psi_{\mathrm{m}} < \Psi_{\mathrm{c}} \tag{1b}$$

$$\alpha(\Psi_{\mathrm{m}}) = 0, \quad \Psi_{\mathrm{m}} < \Psi_{\mathrm{l}} \tag{1c}$$

where Ψ_{c} and Ψ_{l} are the matric potential limits within which the functions are valid. Subscripts c and l refer to 'critical' and 'lower limit', respectively. Eq. (1) dictates that $\alpha(\Psi_{\mathrm{m}})=1$ so long as Ψ_{m} is greater than a critical value of the matric potential, Ψ_{c}, but $\alpha(\Psi_{\mathrm{m}})$ declines linearly to zero at a lower limit, Ψ_{l}. The water stress factor, $\alpha(\Psi_{\mathrm{m}})$, which therefore has no dimension, takes a value between 0 and 1, the former indicating a complete stress (no growth situation) and the latter signifying a stress-free (maximum growth) condition.

Since α is a function of Ψ_{m}, which in turn varies with the soil water content, θ, we require the water retention function which relates Ψ_{m} to θ. Such a relationship can be described according to Campbell (1974) as

$$\Psi_{\mathrm{m}} = \Psi_{\mathrm{e}}\left(\frac{\theta}{\theta_{\mathrm{s}}}\right)^{-b} \tag{2}$$

where Ψ_{e} is the air entry point (kPa), θ_{s} the saturated soil water content ($\mathrm{m}^3/\mathrm{m}^3$) and b the Campbell's parameter (Campbell, 1974). The water content, θ, which also varies with time can be obtained from a water balance (Eq. (12)) presented later.

To formulate a salinity stress index, we note that the electrical conductivity of the soil extract may be converted to the osmotic potential using

$$\Psi_{\mathrm{s}}(\theta) = -40\mathrm{EC}_{\mathrm{sw}}(\theta) \tag{3}$$

where Ψ_{s} is the osmotic potential (kPa) and $\mathrm{EC}_{\mathrm{sw}}$ the electrical conductivity of the soil water (dS/m). As for the Ψ_{m}, $\mathrm{EC}_{\mathrm{sw}}$ (and for that matter Ψ_{s}) varies with θ, so that there is the need to quantify this variation. For soils containing a mixture of highly and slightly soluble salts (as is commonly found in many salt-affected soils), a simple procedure for converting EC_{sw} from one given water content to another was presented by Adiku et al. (1992) as

$$EC_{sw}(\theta) = f\,EC_{ref} + (1 - f)EC_{sss} \tag{4}$$

where EC_{ref} is the reference electrical conductivity value at a known soil water content, θ_{ref}, EC_{sss} is the maximum contribution of the slightly soluble salts to EC_{sw}, and f the concentration or dilution factor (θ_{ref}/θ). Using Eq. (4), the EC_{sw} at any water content can be calculated and this can be converted to Ψ_s using Eq. (3). Thus, at any given θ, Ψ_m (from Eq. (2)) can be directly added to Ψ_s to obtain the total water potential, Ψ_t ($=\Psi_m+\Psi_s$) with the subscript t referring to 'total'. The combined water/salinity stress factor can then be formulated as

$$\alpha(\Psi_t) = 1, \quad \Psi_t > \Psi_c \tag{5a}$$

$$\alpha(\Psi_t) = \frac{\Psi_t - \Psi_l}{\Psi_c - \Psi_l}, \quad \Psi_l < \Psi_t < \Psi_c \tag{5b}$$

$$\alpha(\Psi_t) = 0, \quad \Psi_t < \Psi_l \tag{5c}$$

2.2. Modelling the effect of water/salinity stress on growth

Having obtained an expression for the combined water/salinity stress factor, the next task is to include this factor in a crop model. As we currently lack a bean growth model, a simple empirical growth equation is used to illustrate the task. However, the principle should be generally applicable irrespective of the type of growth model used.

A simple mathematical description of crop growth rate is given by Charles-Edwards et al. (1986) as

$$\frac{dW}{dt} = uW(t)\exp(ut) \tag{6}$$

where u with units kg/(kg s) is the relative growth rate (RGR=$dW/(W\,dt)$) and $W(t)$ (kg) is the weight of the plant at time t (s). Eq. (6) indicates that the growth rate is exponential. However, by considering the self-limiting growth behaviour common to most biological systems, we introduce a factor that drives u to zero as the plant approaches the maximum plant weight (or carrying capacity), W_m, so that Eq. (6) can be re-written as

$$\frac{dW}{dt} = u\left(1 - \frac{W(t)}{W_m}\right)W(t)\exp(ut) \tag{7}$$

Integration of Eq. (7) using the techniques of separating variables leads to an equation that enables the calculation of the total dry weight of the plant at any time as

$$W(t) = \frac{W_0}{kW_0 + (1 - kW_0)\exp(ut)} \tag{8}$$

where k=$1/W_m$ and W_0 is the initial weight of the plant.

To account for the effect of soil water and salinity stress on the plant growth, we introduce $\alpha(\Psi_t)$ into Eq. (6) to calculate the growth rate under stress conditions as

$$\frac{dW}{dt} = \alpha(\Psi_t)u\left(1 - \frac{W(t)}{W_m}\right)W(t)\exp(\alpha(\Psi_t)ut) \tag{9}$$

For a stress-free condition, $\alpha(\Psi_t)=1$, and Eqs. (7) and (9) are identical. If $\alpha(\Psi_t)$ is different from unity but constant, an analytical solution similar to Eq. (9) can still be found since u is constant. However, since $\alpha(\Psi_t)$ varies with soil water content, we calculate the cumulative growth of the plant numerically from

$$W(t) = W(t-1) + dW \tag{10}$$

with dW obtained from Eq. (9) setting dt to unity.

Plant growth and development rate is also temperature dependent (Charles-Edwards et al., 1986). To account for this temperature effect on growth, we express time as thermal time, TT, (°C day) as

$$\mathrm{TT} = T_{av} - T_b; \quad T_b < T_{av} < T_{opt} \tag{11a}$$

$$\mathrm{TT} = (T_{opt} - T_b)\left[1 - \left(\frac{T_{av} - T_{opt}}{T_{max} - T_{opt}}\right)\right]; \quad T_{opt} < T_{av} < T_{max} \tag{11b}$$

$$\mathrm{TT} = 0; \quad T_{av} < T_b \tag{11c}$$

where T_{av} is the average daily temperature, T_b the base or the minimum temperature below which no growth or development occurs, T_{opt} the optimum temperature and T_{max} the maximum temperature above which growth may cease. For many legumes, T_b=10°C (Ellis et al., 1994) and the optimum and maximum temperatures are 34 and 44°C, respectively. The growth constant, u, can then be expressed in terms of thermal time with units kg/(kg°C day).

The cumulative plant dry weight calculated until flowering is assumed to be allocated to the leaf, stem and roots. Thereafter, any additional dry matter is allocated to the pod and seed. At maturity, a seed:pod ratio is then used to calculate the total seed yield.

As indicated earlier, $\alpha(\Psi_t)$ depends on θ which in turn varies with time. The variation θ with time can be obtained from the water balance equation

$$\Delta S_t = I - E_s - T_r - D_r \tag{12}$$

where ΔS_t is the change in water storage (m), I the irrigation (m), E_s the soil evaporation (m), T_r the plant transpiration (m) and D_r is drainage (m). I is measured, and hence, known. E_s is obtained as a product of the maximum measured evaporation from bare soil, E_0, and the ratio of the current soil water content to that at field capacity (Monteith et al., 1989). T_r is estimated using the concept of transpiration efficiency (Tanner and Sinclair, 1983)

$$T_r = W\left(\frac{e^0 - e}{\mathrm{TE}}\right) \tag{13}$$

where (e^0-e) is the vapour pressure deficit, VPD (kPa), and TE is the transpiration efficiency coefficient (kg/kg kPa). For legumes, TE has a value of 0.005 kg/kg kPa (Squire, 1993). The VPD is estimated as the difference between the saturated vapour pressure (SVP) at the maximum and minimum daily temperatures.

With all the terms on the right hand side of Eq. (12) determined, then ΔS_t and hence the change in the soil water content can be calculated to update the soil water content. The equations presented above were used to develop an algorithm, which was programmed in FORTRAN 77 to simulate the growth of beans under variable water and salinity conditions.

3. Materials and methods

3.1. Planting materials and growth conditions

Common bean (*P. vulgaris* cv. Saxa) was grown in greenhouse facilities in Berlin, Germany from February to August 1998. There were two trials, the first extending from February to May and the second from May/June to August. During the first trial, the daily temperatures were low so that the greenhouse was heated to maintain an average temperature regime between 19.8±0.4°C (February/March) and 24.4±0.5 (May). Also, due to low sunlight and short day length conditions during the first trial, the plants were artificially illuminated from 7 a.m. to 7 p.m. by a lighting unit (Model Philips SON-T AGRO 400). During the second trial, sunlight conditions were adequate and the average temperature rose from 25.7±0.7 (May/June) to 28.5±1.1°C by July/August. So, there was no artificial lighting or heating of the greenhouse.

3.2. Soils and treatments

Disturbed soil samples were taken from 0.0 to 0.15 m, A_p horizon of loamy sand (sand=76.9%, silt=16.5% and clay=6.5%) from Dahlem, Berlin. The soil was homogenised by passing through a 2 mm sieve. The soil water retention $\Psi_m(\theta)$ was determined on re-packed soil cores (volume=10^{-4} m^3) using a combination of the tension table and the pressure plate apparatus. The pH of the soil was 6.11 and the electrical conductivity of the saturated paste extract (EC_e) was 0.80 dS/m. The soil had 23.7 mg P/100 g, 8.0 mg K/100 g and 5.98 mg Mg/100 g but negligible N. In the first trial, 60 pots (inner diameter=0.21 m and height=0.15 m) were packed to a bulk density of 1500 kg/m^3 and $CaCO_3$ was applied to each pot at the rate of 1.50×10^{-3} kg. Due to the low inherent soil N, each pot was also applied with 20 ml of NH_4NO_3 (114.3 g/dm^3).

Saline solutions of varying concentrations were prepared from a mixture of NaCl and $CaCl_2$ (ratio of Na:Ca:=1:1) and were added to the pots to obtain a range of ‘saline soils’ (Table 1a). Each pot was seeded with four bean seeds on 6 February 1998 and the seedlings were thinned to two plants at 8 days after emergence (DAE). Field tensiometers and time domain reflectometry (TDR) probes were installed in the pots for monitoring the soil water potential and soil water content, respectively. Two water regimes were imposed at 22 DAE. The first, W_1, involved the liberal watering that maintained the soil water potential at about −5 to –10 kPa (corresponding to soil water content of 0.26–0.23 m^3/m^3) throughout the trial. The second, W_2 maintained the soil water potential of about

Table 1
Treatments

Treatment	Water regime	EC_e (dS/m)	Commencement
(a) First trial			
T_1	W_1	2.33±.09	N/A[a]
T_2	W_1	3.99±.16	N/A[a]
T_3	W_1	5.05±.22	N/A[a]
T_4	W_2	2.44±.05	21 DAE
T_5	W_2	4.50±.10	21 DAE
T_6	W_2	5.991±.69	21 DAE
(b) Second trial			
T_1	W_1	1.76±.19	N/A[a]
T_2	W_1	2.42±.05	N/A[a]
T_4	W_2	2.07±.07	15 DAE
T_5	W_2	3.05±.15	15 DAE

[a] N/A: not applicable; DAE: days after emergence.

-60 kPa, which corresponds to a soil water content of 0.17 m^3/m^3. Together with the salinity treatments, there were six main treatments designated as T_1–T_6 (Table 1a) and these were replicated seven times. All the treatments were arranged in a completely randomised design.

The drained water from each pot was collected in catch cans and re-added to the pots as irrigation, 1 day after each irrigation event. By doing so, the drainage term of Eq. (12) is zero and the total salt content of the pots remained fairly constant through out the experiment. All the pots were weighed at 2–3 day intervals and the soil water content was measured with TDR at each time of weighing.

In the second trial, the total number of treatments was reduced to four, comprising two water and two salinity treatments with each treatment replicated six times. In comparison to the first trial, these treatments correspond to T_1, T_2, T_4 and T_5 although the actual salinity levels differed (Table 1b). In this trial, four bean seeds were planted on 28 May 1998 and thinned to two plants at 6 DAE. The water treatments were imposed earlier (15 DAE) than in the first sowing.

In order to obtain the values for the parameters Ψ_c and Ψ_l in Eq. (1), an additional water treatment, W_3, was introduced in each trial. This water treatment involved the imposition of a 5-day post-flowering drying cycle on triplicate pots that had previously received treatments similar to the control (T_1). During this drying cycle, the pots were weighed and the soil water content also measured 2–3 times daily. The transpiration of the W_3 plants (determined from the weight loss) were related to that of T_1 plants during the drying cycle.

3.3. Data collection and determination of model parameters

Plants from duplicate pots (four plants) for each treatment were harvested at 28 and 49 DAE, and a final harvest was done on triplicate pots (six plants) at 75 DAE in the first trial. In the second trial, T_1 plants were harvested at 38 DAE and at maturity (61 DAE)

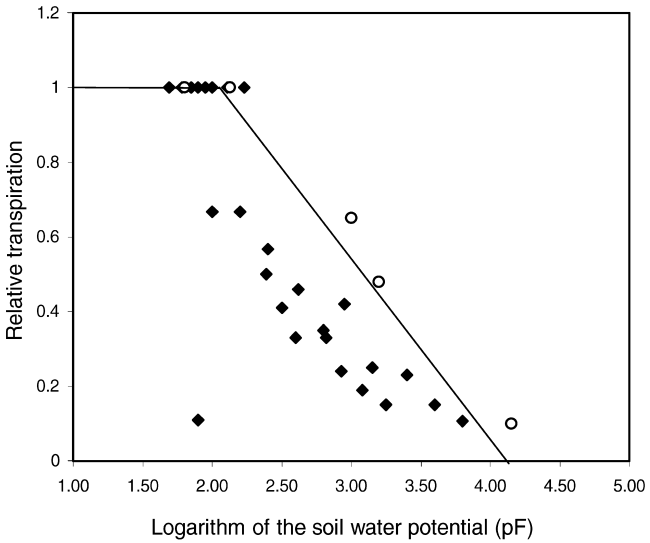

Fig. 1. Relationship between the relative transpiration and the pF ($\log_{10}$) of the total water potential. Closed symbols: first trial and open circles: second trial.

while the plants from all the other treatments were harvested at maturity only. At each harvest, the plant materials were oven-dried at 65°C for 2 days. Seeds were separated from pods prior to oven drying.

The values for the parameters Ψ_c and Ψ_l (Eq. (1)) were obtained from Fig. 1 which relates the relative transpiration to the total soil water potential, Ψ_t. The curve was fitted by the eye in such a way to include as many data points as possible. The value of Ψ_t at which the ratio just falls below unity was taken as Ψ_c and this was found to be pF=2.2 (or −15.0 kPa). Also, the value of Ψ_t at which transpiration ceased (ratio=0) was taken as Ψ_l and this was found to be pF=4.1 (or −1260 kPa).

The soil moisture retention data were used in conjunction with a computer algorithm RETFIT (Hutson and Wagenet, 1992) to obtain the values for the parameters in Eq. (2). The Campbell's b parameter (Campbell, 1974) and the air entry potential Ψ_e were found to be 5.77 and −0.48 kPa, respectively (R^2=0.99). The saturated water content, θ_s, was found to be 0.39 m^3/m^3 and this value was also used as θ_{ref} in Eq. (4). The reference electrical conductivity, (EC_{ref} in Eq. (4)), was taken as the average of the saturated paste extract, EC_e, determined on soil samples taken at all harvests for each treatment. All the soil-input parameters are listed in Table 2a. The other model input required was the irrigation schedule that was different for each of the water treatments and sowings.

The plant parameters W_0, W_m, and u (Eqs. (9) and (10)) were obtained from measurements on bean plants grown under stress-free condition (i.e. T_1) in the first trial only. The value of W_0 obtained on those plants that were thinned soon after emergence and was found to be 1.80×10^{-4} kg. The value of W_m was found to be 1.54×10^{-2} kg and the relative growth rate was 0.0087×10^{-3} kg/(kg°C day). The seed:pod ratio at maturity was found to be 0.70. These data are listed on Table 2b.

Table 2
Model input parameters and their values

Parameter	Symbol	Value
(a) Water and salt balance		
Saturated water content	θ_s	0.39 $m^3 m^{-3}$
Campbell's parameter	b	5.77
Air entry water potential	Ψ_e	−0.48 kPa
Critical water potential	Ψ_c	−1.20 kPa
Lower limit water potential	Ψ_l	−1450 kPa
Reference electrical conductivity	EC_{ref}	Treatment specific
Irrigation	I	Treatment specific
(b) Plant		
Initial plant weight	W_0	1.80×10^{-4} kg
Relative growth rate	u	0.0087 kg/(kg°C day)
Maximum plant weight	W_m	1.54×10^{-2} kg
Seed:pod ratio		0.70

4. Results and discussion

4.1. Simulation of bean growth and water use

Fig. 2a shows the time course of the simulated and the observed total dry weight of beans for the control (T_1) and for T_4 treatments in the first trial. A good agreement between the simulated and the observed is expected for T_1 since the plant parameter values W_0, W_m and u, were derived from this treatment, and this was shown to be the case. Water stress alone (T_4) reduced the dry matter production of beans and the model also correctly simulated this pattern of growth.

Fig. 2b and c show the simulated and observed total dry weight for various combinations of soil water and salinity conditions. Fig. 2b shows that at moderate salinity level under water stress-free conditions (T_2), the reduction in dry matter production was less than that of T_4 (Fig. 2a). A further reduction in growth was observed for the same level of salinity but with water stress (T_5). These trends were also well simulated although the model tended to overestimate the growth at 49 DAE.

High levels of soil salinity treatments (T_3) or salinity and water stress (T_6) resulted in a drastic reduction in the growth of beans (Fig. 2c). The model correctly captured this trend. A comparison of the simulated and observed seed yield for all the treatments pooled (Fig. 2d) gave an R^2 value of 0.92, indicating a fairly good agreement between the simulated and observed.

Fig. 3a shows the time course of the simulated and observed dry weight of beans for treatment T_1 in the second trial. It is evident that the growth rate was faster than in the first trial. At 38 DAE, total dry weight was about 8.5 g per plant whereas during the first trial, the dry weight at 40 DAE was still less than 4.0 g per plant (Fig. 2a). We may note that the experimental conditions, especially the temperature regime in the second trial was much higher than in the first trial so the growth rate was faster in the second trial. The ability of the model to capture this environmental effect could be attributed to the

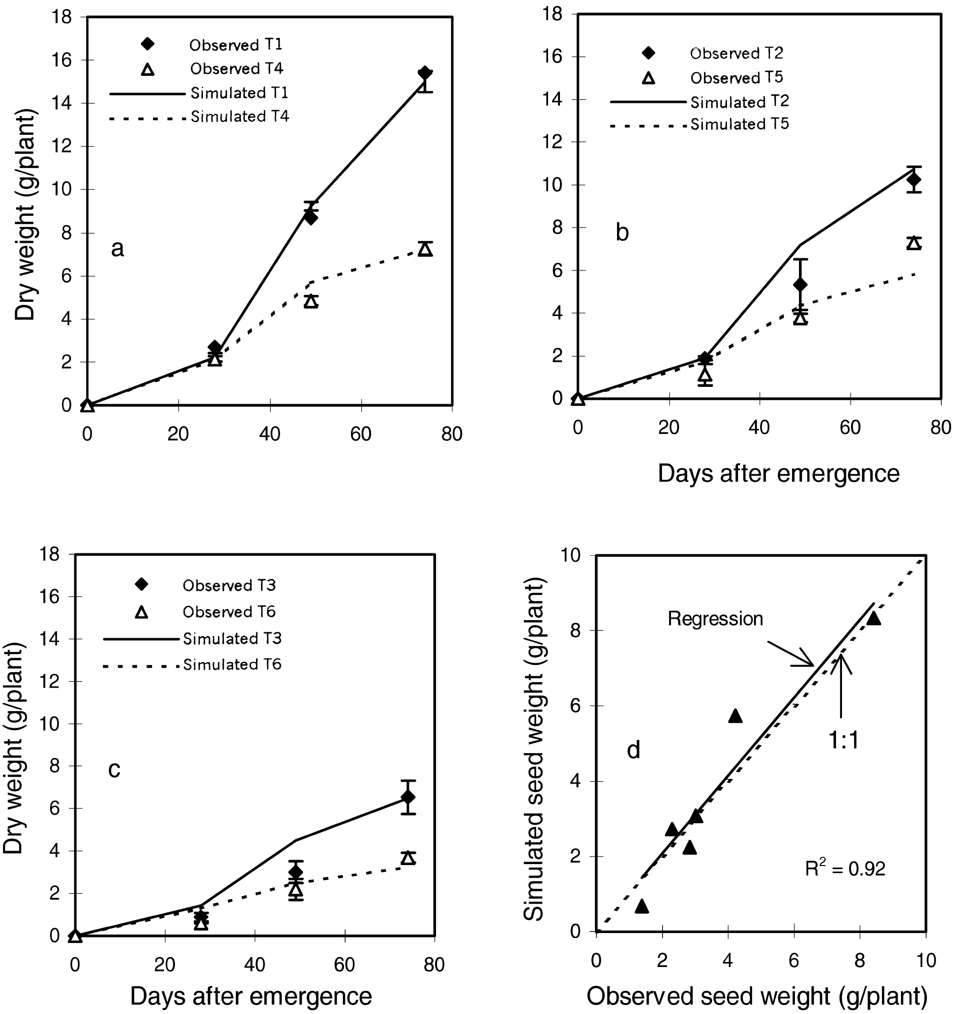

Fig. 2. Time course of the simulated and observed total dry weight of beans under varying soil water and salinity conditions: (a) treatments T_1 and T_4, (b) treatments T_2–T_5, (c) T_3 and T_6, (d) simulated vs. observed seed yield for T_1–T_6.

expression of the growth constant, μ, in terms of thermal instead of chronological time.

Fig. 3b and c show the comparisons between the simulated and observed total dry weight and seed yield, respectively, in the second trial. Generally, the model simulations of both the dry matter (R^2=0.85) and seed yield (R^2=0.89) were quite good. The RMSE values were 0.91 and 0.51 g per plant for the total dry weight and seed yield, respectively, which are quite low, indicating that the average deviation of the simulated from the observed was small.

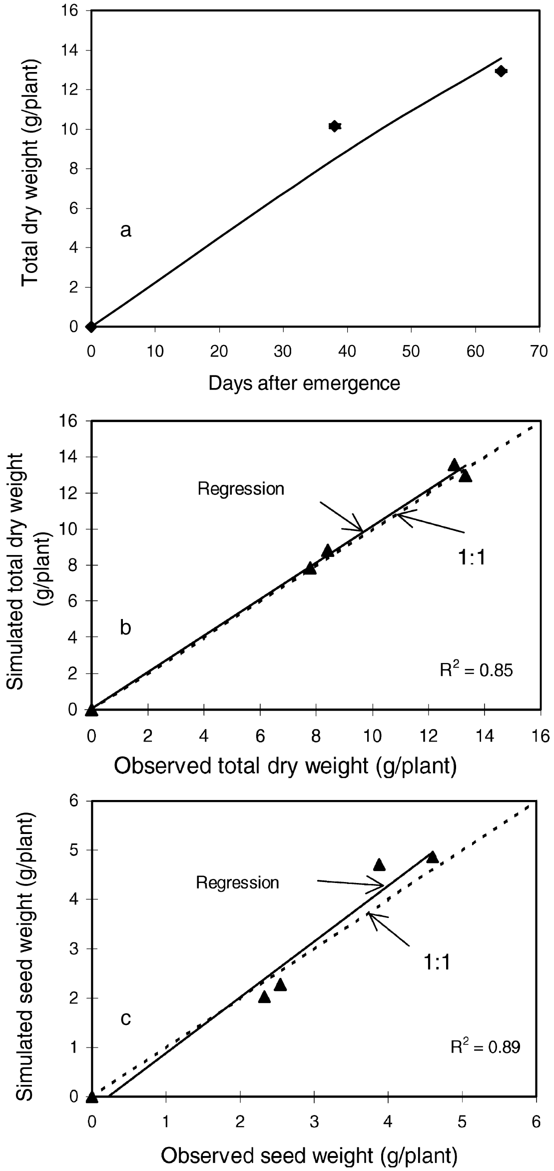

Fig. 3. Time course of the simulated and observed total dry weight of beans in treatment T_1 of the second trial: (a) a comparison of simulated and observed total dry weight (b) and seed yield (c) of beans grown under grown under varying soil water and salinity conditions in the second trial.

Fig. 4a presents the comparison between the simulated and observed total water use by bean plants under the various water and salinity treatments during the first trial. The control treatment T_1 used the highest amount of water (3.66 kg per plant) from sowing to maturity. Total water use decreased with increasing water and/or salinity stress. The

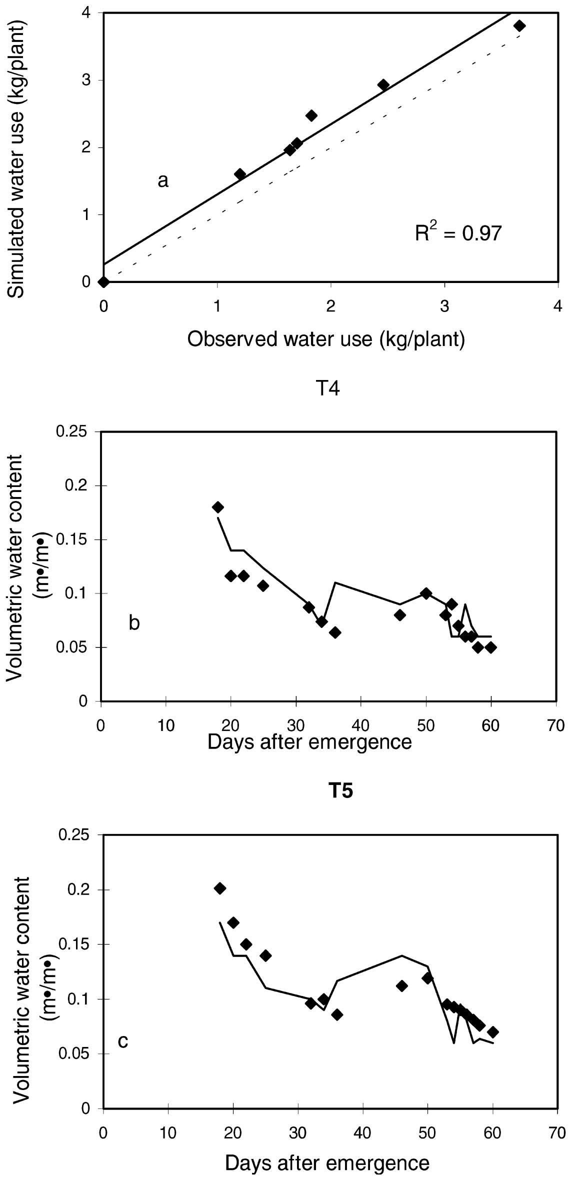

Fig. 4. Comparison between the simulated and observed total water use: (a) simulated (lines) and observed (symbols) variation of the soil water content with time for treatments T_4 (b) and T_5 (c) during the first trial.

treatment T_6 had the lowest water use (1.19 kg per plant). The simulated water use followed the same trends as observed. For treatment T_1, a total water use of 3.81/kg plant was simulated while the total water use of 1.57 kg per plant was simulated for treatment T_6. Despite the good agreement between the observed and simulate trends (R^2=0.97), all the simulated data lie above the 1:1 line indicating that the model consistently overestimated water use.

Fig. 4b and c show examples of the variation of the simulated and observed water content with time for treatments T_4 (water stress only) and T_5 (combined water and moderate salinity stress) during the first trial. For treatment T_4, the soil water content declined sharply from about 18% at 20 DAE to about 7% at 35 DAE and thereafter remained near this level until 60 DAE. The simulated water content followed the observed trend but there were some discrepancies between 38 and 48 DAE. In the case of treatment T_5, the simulated water content also follows that observed but again the model overestimated between 30 and 40 DAE.

4.2. Model performance, limitations and improvement needs

The results indicate a generally good agreement between the simulated and observed growth of beans under the varied soil water and salinity test conditions. This signifies that the combined water/salinity stress factor was capable of modifying the growth of beans under the test conditions. Apparently, the approach of formulating the stress factor in terms of soil water potential is useful and practical and is easy to include in crop models. We may note that most crop models are invariably complex, hence, it is desirable to add only new simple routines. Although the model was tested on beans alone, the approach is process-related and may be applied to other crops.

However, the model, in its present form, has certain limitations. Firstly, the conversion procedure (Eq. (4)) of Adiku et al. (1992), though pragmatic, does not consider the changes in soil composition in detail. An improvement of the model in this respect would require a more detailed description of the variations in soil solution composition with changing soil water content since the EC_{sw} will be affected by the solution composition. Secondly, for soils with appreciable clay content, the effect of ion–colloid interactions on the soil solution composition also needs to be taken into account when estimating the variation of the electrical conductivity with soil water content. Thirdly, the use of one constant value for the pore distribution parameter, b, in Campbell (1974) equation (Eq. (2)) may be erroneous since it is known that this parameter can be altered by salinity due to swelling of the clay (Russo and Bresler, 1980). Variations in b need to be considered when calculating the matric potential of the soil water, Ψ_m. Finally, the extension of the model to field conditions would require field scale water and salt balance.

5. Conclusions

We have presented a simple model that is capable of simulating the effects of water and salinity stress on the growth of beans. The model relies on the principle that a combined water and salinity stress factor can be derived from the total water potential (matric and osmotic potentials). This stress factor is used as a growth modifier in a simple logistic growth equation. The simulated and the observed growth of beans agreed quite well under a range of water and salinity conditions with R^2 ranging from 0.89 to 0.94 while the agreement between the simulated and observed seed yield was also good (R^2=0.85–0.92).

The model was, however, tested only under greenhouse conditions and the extension to field scale will require the use of field-scale water and salt balance equations.

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