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Adapting the CROPGRO model for saline soils: the case for a common bean crop

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Abstract Water scarcity and severe environmental degradation are causing water managers in the Fergana Valley, Uzbekistan to re-evaluate irrigation water use. Crop models could play an important role in helping farmers decide which systems (crops and irrigation technologies) are feasible. CROPGRO is a physiologically robust agronomic model, although the current version does not consider the effects of soil salinity on crop water use or growth. CROPGRO was modified to include a salinity response function and was tested for gypsiferous soils. A qualitative analysis of the model indicated the model performed as expected under a range of atmospheric, irrigation and crop tolerance scenarios. Model simulations compared very favourably for common bean (*Phaseolus vulgaris*) to results obtained in the greenhouse for yield and seasonal crop evapotranspiration with values of the Willmott agreement index (i) of 0.98 for both variables evaluated at different levels of salinity and deficit irrigation. Final biomass predictions were less satisfactory, although the modified model performed as well as the original model. The modified model was successfully tested with field data on common bean from an experiment in the Fergana Valley (i of 0.75 for ET and 0.74 for final yield), although the sensitivity of the model to a soil fertility function and relative nodule number made it difficult to assess the model performance.

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Introduction

Increasing food insecurity and competition for scarce water resources in the Fergana Valley of Uzbekistan are forcing agricultural water users in the region to re-evaluate irrigation practices. Despite high irrigation requirements, cotton and winter wheat are the main crops produced in the country. Farmers are required to produce these crops in a state order system, as cotton exports generate close to one-third of the country's gross domestic product. However, the extent and degree of soil salinization increases each year due to rising water tables associated with heavy leaching. As such, efforts to improve food security by introducing short season grain legumes grown after winter wheat harvest, as proposed by Webber et al. (2006) and Bourgault (2008), should respect farmer's constraints on food crop production: (1) needing to produce cotton and/or winter wheat, (2) increasing soil salinity and (3) having little available water (priority crop is cotton). A number of inexpensive and easy-to-implement improvements to the region's predominant surface irrigation systems have been identified and result in water savings (Horst et al. 2005,

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2007; Webber et al. 2006). Crop models could play an important role in allowing farmers and planners to decide which systems (crops and technologies) are feasible.

CROPGRO (Boote et al. 1998; Jones et al. 2003), a physiologically-based agronomic model, was originally developed for legumes and is widely used. It is one of two primary crop models (the other being CERES by Ritchie and Otter 1985) in the decision support system for agro-technology transfer (DSSAT) software package. DSSAT manages soil, weather, and management and crop data-bases to simulate various agricultural and climatic scenarios over multiple years. DSSAT can simulate 27 different crops, is over 15 years old and has been applied in over one hundred countries. Currently, the DSSAT models do not include the effects of soil salinity on crop growth, although Castrignano et al. (1998) proposed a salinity response factor for CERES-Maize using pre-dawn leaf water potential. This is a serious limitation for its application in regions such as Uzbekistan.

Plant response to salinity is proposed by some authors (Munns and Termaat 1986; Munns et al. 2000) to encompass two phenomena; water deficits which affect the plant immediately, and specific ion toxicity effects are noticeable weeks to months later, after thresholds of specific ions in leaf tissue are surpassed (Munns et al. 2000). Water deficit effects are caused by the osmotic potential, due to salts or other osmotica (Yeo et al. 1991), as perceived by the roots, and result in reduced cell elongation rates, with greater reductions occurring in the shoot than root cells (Munns and Termaat 1986). Others have determined that Na^+ does induce an immediate reduction in leaf elongation rate, in addition to water deficit effects, before any increase in leaf Na^+ concentrations are detected (Montero et al. 1998). Montero et al. (1998) found, at equivalent osmotic potentials, greater reductions in growth rates and increased xylem ABA concentrations with NaCl than concentrated nutrient solutions. However, some work shows that many symptoms of Na^+ toxicity are actually due to Ca^{2+} deficiency as salinity inhibits Ca^{2+} uptake when the Na^+/Ca^{2+} ratio is high (Greenway and Munns 1980; Maas and Grieve 1987). This could be the case in the Montero et al. (1998) study. Calcium can moderate the effects of sodium salinity, attenuating growth reductions (Eaton 1942; Maas and Grieve 1987) and is required for root membrane integrity and proper function of ion transport systems (Lauchli and Epstein 1970). The presence of calcium in gypsiferous soils of the Fergana Valley, Uzbekistan (Szabolcs 1989) is believed to moderate the toxic effects of sodium salts, by protecting root membrane functioning and preventing calcium deficiency. Therefore, an approximate salinity response factor, in gypsiferous soils under conditions of low to moderate soil salinity, could act to increase water stress at a given soil water content, particularly for short season crops that may avoid the longer term specific ion effects.

Various hydrological-based models, which determine water and solute flow in the soil from numerical solution of Richard's equation and the convection-dispersion equation, account for salinity effects in the way in which root water uptake, RWU, is handled. In these models, two general approaches are used to simulate RWU. The microscopic approach was first formulated by Gardener (1964) and considers the physics of water flow through soil micropores. The macroscopic approach is based on the empirical reduction function, $\alpha(h,h_o)$, which reduces water uptake from a maximum (usually potential plant transpiration) in response to lowered soil water potential, where h is the soil water pressure head, and h_o is the soil water osmotic head (Feddes et al. 1976; van Genuchten 1987; Cardon and Letey 1992b; Homaee et al. 2002b). In a comparison of the microscopic model of Nimah and Hanks (1973) and the macroscopic model of van Genuchten (1987), the macroscopic model was judged to be much more representative of actual root water uptake in response to salinity stress (Cardon and Letey 1992a). The microscopic model of root water uptake was unresponsive to salinity when the soil water content was high, and root water uptake decreased quickly to zero as the soil dried. Cardon and Letey (1992a) explain this as being due to the large dependence of the root water uptake term on soil conductivity which changes sharply with changes in soil water content, masking the salinity response.

Within the macroscopic models of root water uptake, different methods exist for determining the relative effects of water and salinity, including additive (van Genuchten 1987; Cardon and Letey 1992b) and multiplicative effects (van Genuchten 1987; Skaggs et al. 2006), as well as hybrids or combinations of these types (Homaee et al. 2002b). In a comparison of six types of macroscopic uptake terms, Homaee et al. (2002a) determined that the use of an additive term (van Genuchten 1987) resulted in the worst match performance in all cases. Likewise, Shalhevet and Hsiao (1986) concluded the effect of water stress to be twice that of salinity stress with an equivalent soil water potential, raising questions about the validity of an additive approach. Homaee et al. (2002a) found their own multiplicative combination reduction model (Homaee et al. 2002b) performed best under almost all circumstances. The combination reduction function proposed by Homaee et al. (2002b) is given by:

$$\alpha(h, h_o) = \frac{h - (h_4 - h_o)}{h_3 - (h_4 - h_o)} \times \left[1 - \frac{a}{3.6}(h_o^* - h_o)\right] \qquad (1)$$

where h is the soil water pressure head, h_o is the soil water osmotic head, h_4 is the soil water pressure head corresponding to the permanent wilting point, h_3 is the soil water

pressure head where soil water uptake starts to be reduced, h_o^* is the threshold osmotic head where yields start to decline due to salinity, a is the relative decline in water use per unit of increasing salinity (% dS m^{-1}), and 3.6 is a conversion factor, to convert between osmotic head and dS m^{-1} (US Salinity Laboratory Staff 1954). The two terms in their reduction function coincide with the water stress reduction factor of Feddes et al. (1976) and the salinity reduction factor of Maas and Hoffman (1977). The Homaee et al. (2002b) model is similar to that of van Dam et al. (1997) except that Homaee et al. (2002b) changed the soil water head corresponding to the permanent wilting point, h_4, so that it increased with increasing salinity by adding h_o to h_4. The Maas and Hoffman (1977) reduction function was formulated to relate soil salinity to relative yield, not ET or root water uptake. However, the general form of the model should be valid if reductions in yield roughly parallel reductions in water uptake with the appropriate yield response factor (Doorenbos and Kassam 1979) and appropriate choices of the constants a and h_o^* (Green et al. 2006). Homaee et al. (2002b) appear to apply directly the coefficients from Maas and Hoffman (1977) and cite the availability of these coefficients for a wide variety of crops as the main reason for choosing this particular salinity reduction function over others (van Genuchten 1987; Dirksen and Augustijn 1988) with harder-to-obtain parameters.

From the literature cited above, it is clear that different approaches exist to model root water uptake in response to soil salinity. However, most of the hydrological models include only very elementary crop model routines that ignore climate, management and genetic factors that govern crop growth. The crop growth model CropSyst (Stöckle et al. 2003) does consider soil salinity. The model considers solute transport in the soil water profile with a numerical solution of Richard's equation and a convection equation, enabling the calculation of the soil water osmotic potential (Ferrer-Alegre and Stöckle 1999). The salinity effects in the model are conceptually very similar to that in Homaee et al. (2002b) in that there is an empirical salinity reduction function and osmotic and matric potentials are added together reducing the total water potential gradient between soil water and root (an effect that is similar to changing the permanent wilting point). The main difference is that the salinity reduction function used is the S-shaped curve of van Genuchten (1987) rather than the linear response of Maas and Hoffman (1977). In all of the models reviewed, the assumption is made that salinity effects are limited to water deficit effects, and no toxic ion effects are included.

The goal of this research is to assess the potential of using CROPGRO as a planning tool in regions with soil salinity. The specific objectives were to (1) modify the existing root water uptake routines to account for soil salinity; (2) compare the original and modified model in their ability to correctly predict yield and water use under saline conditions; and (3) evaluate the modified model for predicting crop growth in Uzbekistan under conditions of water stress by comparing simulations to field data.

Model description

CROPGRO is well documented (Boote et al. 1998; Jones et al. 2003). Only aspects related to root water uptake, water stress and proposed salinity response factor are discussed below.

A tipping bucket approach is used in CROPGRO and the DSSAT suite of crop models to determine water infiltration and soil water content in successive soil layers. Water drains to the next layer when the soil water content is above the drained upper limit (equivalent to field capacity) or can be simulated as upward flow when the soil is saturated in layers below, depending on the soil hydraulic conductivity (Ritchie 1998). Many soil water parameters can be estimated by DSSAT based on soil texture (Ritchie 1998). All water balance calculations are constrained to the user-specified root zone depth, which is generally error prone due to measurement uncertainties. While CROPGRO does not use a process-oriented approach to describing soil water flow, the potential root water uptake term, $RWU_p(L)$, for each soil layer L, is very similar to the microscopic uptake term of Gardener (1964) and is given by:

$$RWU_p(L) = \min\left(\frac{C_1 e^{\min(40, C_2(SW(L)-LL(L)))}}{C_3 - \ln(RLV(L))}, RWUMAX\right) \times DLAYR(L) \times RLV(L) \qquad (2)$$

where $RWU_p(L)$ is in cm day^{-1}, C_1 is an empirical constant ($C_1 = 0.00132$), C_2 is given by $120-250*LL(L)$ where $LL(L)$ is the lower limit of plant available water corresponding with the permanent wilting point (cm^3 [water] cm^{-3} [soil]), $SW(L)$ is the actual soil water content (cm^3 [water] cm^{-3} [soil]), C_3 is an empirical constant ($C_3 = 7.01$), $RLV(L)$ is the root length density for soil layer L (cm [roots] cm^{-3} [soil]), $RWUMAX$ is the maximum root water uptake per unit length of root (cm^3 [water] cm^{-1} [root]), and $DLAYR(L)$ is the depth of layer L (cm). The total potential root water uptake, $TRWUP_p$, is equal to the sum of $RWU_p(L)$ for all soil layers.

Total actual root water uptake, $TRWUP$, is the minimum of potential crop transpiration, E_{op}, and total potential root water uptake, $TRWUP_p$. E_{op} is the product of the reference crop evapotranspiration (ET$_o$) (the FAO Penman–Monteith equation was used) and a term representing the fraction of the solar irradiance captured by the plant canopy, such that:

$$E_{op} = ET_0 \times \left(1 - e^{-0.7 \times LAI}\right) \qquad (3)$$

where LAI is the leaf area index.

The original CROPGRO model calculates three water stress factors when the actual evapotranspiration changes in relation to potential evapotranspiration. The first water stress factor, $TURFAC$, is associated with leaf turgor and reduces expansive growth, when total potential root water uptake is <1.5 times the potential transpiration (Ritchie 1998; Jones et al. 2003). $TURFAC$ is computed as:

$$TURFAC = \frac{TRWUP_p}{1.5 E_{op}} = \frac{TRWUP_p}{1.5\, ET_0 \times \left(1 - e^{-0.7 \times LAI}\right)}. \qquad (4)$$

The water stress factor for reducing photosynthesis, SWFAC, acts when total potential root water uptake is less than potential transpiration (Ritchie 1998; Jones et al. 2003) and is given by:

$$SWFAC = \frac{TRWUP_p}{E_{op}} = \frac{TRWUP_p}{ET_0 \times \left(1 - e^{-0.7 \times LAI}\right)} \qquad (5)$$

The third water stress factor acts to increase biomass partitioning to the roots when the ratio of actual transpiration relative to potential transpiration is <1 (Hoogenboom et al. 1992).

Modifying the CROPGRO code to simulate water uptake under conditions of soil salinity presents two main challenges. First, the literature indicates the superior performance of the macro-scale empirical reduction functions in simulating water uptake under saline conditions, but the CROPGRO root water uptake function employs a microscopic approach. The function is designed to predict water uptake in dry soil conditions, as water uptake is not considered limiting under wet soil conditions. The root water uptake function predicts erroneously high values of water uptake when the soil water content is high (Ritchie 1998). This is not a problem for the original CROPGRO model as total actual root water uptake is the minimum of total potential root water uptake and potential ET. However, this approach made it impossible to implement a salinity reduction function in all but the driest soils. For example, a 10% reduction in water use for an erroneously high estimate of water uptake is still an erroneously high value of water uptake! Thus, modifications to the root water uptake computations were needed to develop an appropriate salinity response.

Secondly, when the soil was dry and saline, a second reduction factor was needed to ensure stomatal closure was greater under saline than non-saline conditions. With the initial hypothesis that salinity effects could be modelled as only water deficit, this second reduction factor was not included with the result that yields increased under salinity if water stress was also experienced! This unrealistic result was caused by a feedback of lower LAI (due to salinity)

resulting in a smaller value of the denominator of SWFAC (Eq. 5), and therefore less photosynthetic stress. This problem was not reported for the hydrological models, although they contain only very elementary crop growth models, and it is unclear if they considered this feedback. This topic is elaborated upon in the qualitative analysis section.

Before outlining the modifications to the CROPGRO routines, the following list summarizes the main assumptions and assertions of the modified model:

- Soil salinity may vary with depth in the soil.
- Soil salinity is considered constant within the growing season.
- When soil salinity is less than the crop tolerance, root water uptake will be determined by the original CROPGRO routines.
- Soil salinity should reduce plant water uptake from a potential uptake by an amount equivalent to a reduction function dependent on soil salinity ($SALT(L)$) and crop characteristics of tolerance ($EC_{threshold}$) and relative rate of reduction in water use due to salinity ($SALRDCT$).
- Soil salinity will not reduce plant growth when the soil is *very* moist (i.e. when the daily total potential root water uptake calculated by the original CROPGRO model is >1.5 times the rate of potential ET, E_{op}).
- When the soil is moist (i.e. when the daily rate of total potential root water uptake calculated by the original CROPGRO model is greater than E_{op} and <1.5 times the rate of E_{op}), potential root water uptake in each layer will be defined by the potential rate of ET, E_{op}, multiplied by the proportion of the total water uptake from that layer.
- When the soil is dry (i.e. when the daily total potential root water uptake calculated by the original CROPGRO model is less than E_{op}), the original CROPGRO routine will be used to simulate potential root water uptake, as it has been designed for these conditions.
- At any given soil water content, saline conditions should result in greater stomatal closure and reductions in photosynthesis than non-saline conditions. This implies that salinity should cause SWFAC to be less than (or at least equal to) SWFAC under non-saline conditions, all other factors equal.
- The salinity routines are tested using saline soils dominated by gypsum salts, although they are expected to work for all low to moderately saline soils with appropriate parameterization.

Therefore, for conditions of soil salinity, an iterative routine was implemented, that replaced $LL(L)$ with a new value $LL_{salt}(L)$ for the calculation of $RWU_p(L)$. It is important to note that $LL_{salt}(L)$ was not passed to any other routines in CROPGRO. The first step was to calculate

$RWU_p(L)$ and $TRWUP_p$ using the original model. This initial calculation was used to (1) determine if soil water or E_{op} limited water uptake and (2) to determine the proportion of water uptake from each layer, $PWU(L)$, calculated as:

$$PWU(L) = \frac{RWU_{previous}(L)}{TRWUP_{previous}} \quad (6)$$

where $RWU_{previous}(L)$ and $TRWUP_{previous}$ indicates values of these variables determined in the previous iteration and are used to determine $PWU(L)$, which is then used to determine new estimates of $RWU_p(L)$ and $TRWUP_p$.

For wet soils ($TRWUP_{p, initial} > E_{op}$), actual $TRWUP$ is set equal to $ET_{reduced}$. Hence, $LL_{salt}(L)$ is calculated as follows:

$$LL_{salt}(L) = SW(L) - \frac{1}{C_2(L)} \left[\ln \left(\frac{PWU(L)}{DLAYR(L) \times RLV(L)} \right. \right.$$
$$\left. \left. \times ET_{reduced} \times \left(\frac{C_3 - \ln(RLV(L))}{C_1} \right) \right) \right] \quad (7)$$

where

$$ET_{reduced} = \left(1 - \frac{SALRDCT}{100} (SALT(L) - EC_{threshold}) \right)$$
$$\times E_{op} \quad (8)$$

where $SALRDCT$ (%/dS m^{-1}) is the relative rate of reduction in water use with increasing soil salinity, $SALT(L)$ is the soil salinity (dS m^{-1}), and $EC_{threshold}$ (dS m^{-1}) is the soil salinity above which plant water use will be suppressed. Using $LL_{salt}(L)$, new estimates of $C_2(L)$, $RWU_p(L)$ and $TRWUP_p$ are calculated. If the new value of $TRWUP_p$ is within 0.1 mm of $ET_{reduced}$, the process is terminated. Otherwise, the calculation is repeated beginning with an updated value of $PWU(L)$. The process usually converged after two to three iterations.

In dry soils, the same iterative process is applied except that a value of $LL_{salt}(L)$ is desired that would result in values of $RWU_p(L)$ that would sum to the original model estimate of $TRWUP_{p,initial}$, multiplied by the salinity response function. $LL_{salt}(L)$ is calculated using Eq. 7 with $ET_{reduced}$ replaced with the total salinity-reduced water uptake, $TUP_{salinity\_red}$, where

$$TUP_{salinity\_red} = TRWUP_{p, initial}$$
$$\times \left(1 - \frac{SALRDCT}{100} (SALT(L) - EC_{threshold}) \right) \quad (9)$$

Additionally, when the soil was dry and saline, a second reduction factor was needed to ensure stomatal closure was greater under saline than non-saline conditions. Under these conditions, $SWFAC_{saline}$ is calculated as:

$$SWFAC_{saline} = SWFAC$$
$$\times \frac{1}{S_1 (SALT_{average} - EC_{threshold}) + S_2} \quad (10)$$

where $SALT_{average}$ is the average soil salinity in the root zone, and S_1 and S_2 are parameters adjusted to obtain good model fit with observed data. The initial estimates of S_1 and S_2 were obtained by fitting a regression line between points representing the reduction in $SWFAC_{saline}$ needed to make $SWFAC_{saline}$ at least as small as in soils with the equivalent soil water content (and no salinity) and the difference between $SALT_{average}$ and $EC_{threshold}$. Further adjustment was performed to obtain the expected reduction in water use at the given soil salinity. A flow chart outlining the major modifications to the root water uptake routine is presented in Fig. 1.

Model evaluation

Qualitative analysis

Version 4.0.2.0 of the DSSAT shell (2005) was used for all of the simulations, and the changes to the CROPGRO Fortran code were made using Compaq Visual Fortran Professional Edition 6.6.0. Having built a salinity response into CROPGRO, a number of hypothetical simulations were run to see if the model could capture the general trends in yield and water use expected with increasing soil salinity. As in the analysis of Ferrer-Alegre and Stöckle (1999), the model response to different levels of deficit irrigation, water vapour pressure deficit (VPD) and cultivar salinity tolerance, all of which are reported to change the response to salinity for specific crops (Francois and Maas 1999), were qualitatively evaluated. The model was tested with respect to these factors using the common bean cultivar and climatic conditions used in the greenhouse study (Bourgault 2008; Webber et al. 2008). As baseline conditions, a VPD equivalent to that used in the greenhouse study, which attempted to mimic the field conditions in the Fergana Valley of Uzbekistan in the mid to late summer, was selected. The default level of deficit irrigation corresponded to a 50% depletion of the readily available water. The default crop values are a salinity threshold of 4.8 dS m^{-1} as determined for the cultivar of common bean used in the greenhouse study in gypsiferous soil with a reduction factor of 4.6%/dS m^{-1}. For the simulation, varying the level of deficit irrigation between depletion factors of 30 and 80% was selected. The VPD was varied from the value estimated for the greenhouse by 20% greater than and less than that value. A salt-sensitive common bean crop (in gypsiferous soil) was estimated to have a salinity threshold of 3 dS m^{-1} and a relative

Fig. 1 Flowchart of the modified model for computing the influence of soil salinity on the total root water uptake
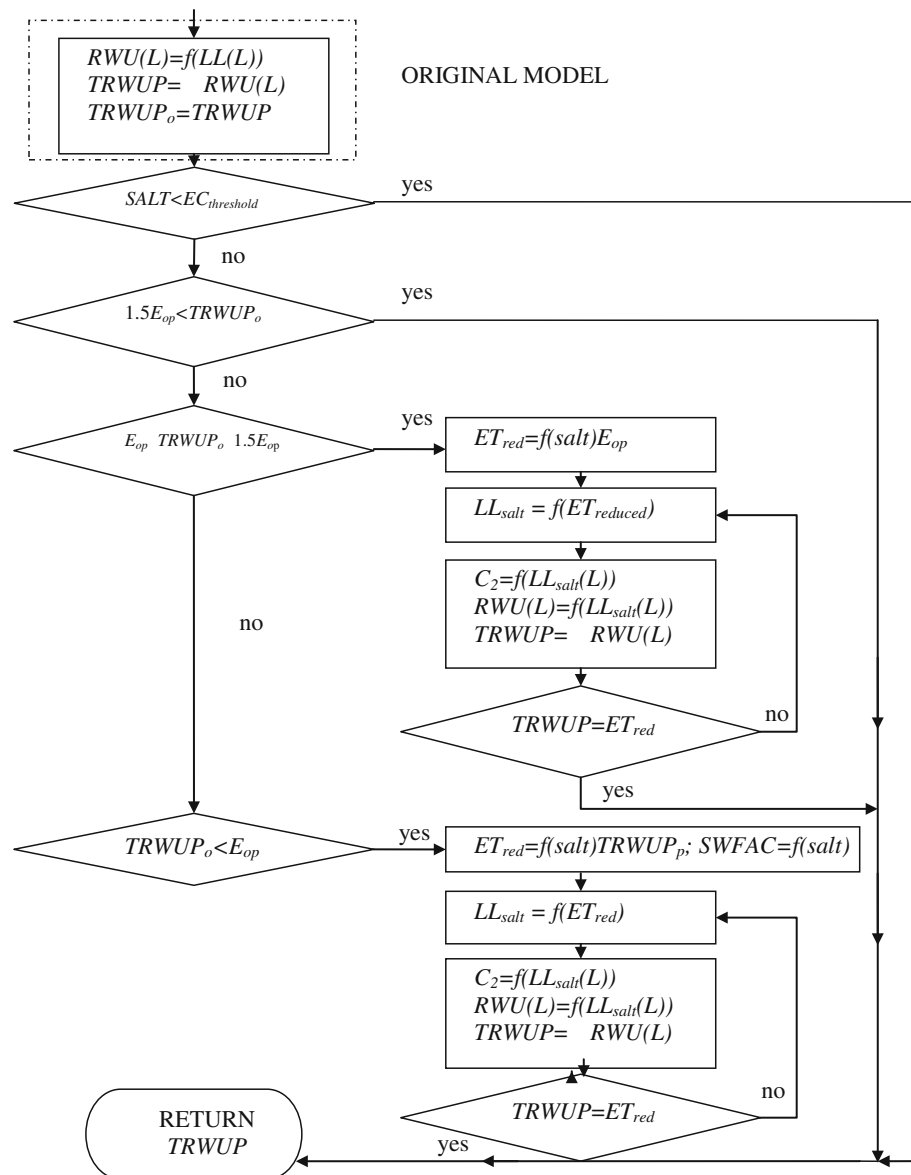
reduction rate of 10%/dS m^{-1}, and the tolerant cultivar was estimated to have a salinity threshold of 6 dS m^{-1} and a relative reduction rate of 3.5%/dS m^{-1}. Six levels of soil salinity were simulated, ranging from 2.8 dS m^{-1} (corresponding to gypsum salts only) to 15 dS m^{-1}.

Quantitative analysis

Two experiments were used to evaluate the model performance. The first experiment (Bourgault 2008; Webber et al. 2008) was conducted in a greenhouse on the Macdonald Campus of McGill University, Montreal, Canada during the spring and summer of 2007. In this experiment, soil salinity and deficit irrigation level comprised the main treatments to determine the crop response to increasing salinity in a soil dominated by gypsum salts. An Uzbek

variety of common bean was grown in large soil bins measuring 0.43 m wide by 0.74 m long by 0.50 m deep, at an initial density of 20 plants per bin. The bins, which were drained along their length by 5 mm perforated drain pipe, were filled with a Soulanges fine sandy loam soil (67% sand; 20% silt; and 13% clay). Gypsum (CaSO$_4$·2H$_2$O) and NaCl were added to the soil with a small portable cement mixer to give EC$_e$ values of 2.8 dS m^{-1} (no NaCl), 5.4 dS m^{-1}(low NaCl) and 7.5 dS m^{-1} (high NaCl). The boxes were irrigated with one of three levels of deficit irrigation, roughly corresponding to depletion levels of 45, 60 and 70%. The greenhouse air temperature was 32°C during the day and 20°C at night with the photoperiod set at 14 h per day. The entire experiment was conducted twice. A complete description of the methodology is found in Bourgault (2008) and Webber et al. (2008).

The second experiment was conducted in the field, in the Fergana Valley of Uzbekistan (40°23′N, 71°45′E) during the summers of 2003 and 2004. This experiment was designed to determine the crop response of a local variety of common bean to deficit irrigation and alternate furrow irrigation grown as a second crop after winter wheat harvest. The same seed stock was used in both greenhouse and field experiments. The soil type ranged between sandy loam and silt loam. The average salinity of the fields was 5.8 dS m^{-1}, with the dominant salt being gypsum. Each plot measured 15 m by 15 m and contained 23 furrows 12 m in length and was replicated four times. Deficit irrigation levels were the same as in the previous experiment. A Vantage Pro meteorological station (Davis Instruments Corp., Hayward, USA) in an adjacent field measured daily minimum and maximum air temperature and relative humidity, wind speed at 2 m and precipitation. These parameters, together with sunshine hours from a weather station located 25 km from the field, were used to estimate ET_o. The root zone was taken as 0.6 m, and soil water content was measured gravimetrically at the soil surface, 0.1 and 0.2 m, and with a neutron probe at 0.4 and 0.6 m 2 days before and after irrigating and every 5–7 days to calculate the water balance and determine crop consumptive water use. Full experimental details are in Webber et al. (2006) and Bourgault (2008).

In both experiments, destructive samples were taken four times during the growing period from two plants per plot to determine different components of above-ground biomass and leaf area. Seed harvest was conducted at physiological maturity to determine the various yield components and threshing percentage.

Initial model calibration for the cultivar traits was performed with the non-saline treatments (three levels of deficit irrigation) in the first greenhouse trial following the methodology outlined by the model developers (Boote 1999). Validation for the non-saline treatments was performed with the same treatments from the second greenhouse trial. Since all of the soil bins contained gypsum (as does the soil in the region studied in the Fergana Valley), any osmotic effects due to the gypsum only will appear in the soil fertility factor (SLPF). This factor is used to describe reductions in photosynthesis due to any soil nutrient deficiencies other than nitrogen. Calibration for the salinity response was performed using all nine treatments (three salt levels and three levels of deficit irrigation) from the first greenhouse trial. Model validation was performed with the second trial from the greenhouse and the two field experiments from Uzbekistan.

The evaluation criteria used were the root mean squared error (RMSE), the mean absolute error (MAE), the relative error (RE) and the Willmott (1981) agreement index (i). All measures are defined in Wallach (2006) and when used

in combination with graphical representation of the simulated and observed variables provided sound evidence for evaluating and modifying models (Willmott 1981; Wallach 2006).

Results and discussion

Qualitative analysis

The results of the qualitative analysis, for yield and water consumption, are shown in Figs. 2 and 3, respectively. In these, yield and water consumption are expressed relative to the 2.8 dS m^{-1} salinity level and the (a) 30% depletion irrigation factor, (b) typical VPD and (c) average crop salinity tolerance. The model is responsive to soil salinity under various levels of deficit irrigation. The effects of soil salinity are less severe in humid conditions, and greater yield reductions are expected with higher VPDs (Francois and Maas 1999). Finally, different crop tolerances for salinity are captured with changes in the threshold salinity level and the relative reduction factor. In all cases, the relative reductions in final yield are greater than the corresponding reductions in water use. This highlights the discrepancy between the threshold (A) and the relative reduction (B) coefficients of the Maas and Hoffman (1977) reduction function for yield being applied directly in the proposed reduction function root water uptake, as appears to have been the case with Homaee et al. (2002b). For the simulations run for this study, values of the salinity threshold for water use ($EC_{threshold}$) and the relative rate of reduction in water use (SALRDCT) obtained from extrapolation of data collected in the greenhouse trial with the cultivar under consideration were used. However, Allen et al. (1998) combine the yield response to water stress factor, K_y, of Doorenbos and Kassam (1979) with the Maas and Hoffman (1977) salinity yield reduction function, (B), to obtain an "effective" relative water use reduction factor, b, which serves the same function as the variable SALRDCT, where

$$b = \frac{B}{K_y} \tag{11}$$

This may be a good first approximation to be included as a species default for SALRDCT in CROPGRO. However, for the common bean cultivar considered here, grown in a gypsiferous soil, the value of b (called SALRDCT in the modified CROPGRO) obtained from Eq. 11 and constants for common bean from Doorenbos and Kassam (1979) and Maas and Hoffman (1977) was more than three times greater than the value of SALRDCT obtained in the greenhouse trial and found to work well in the model.
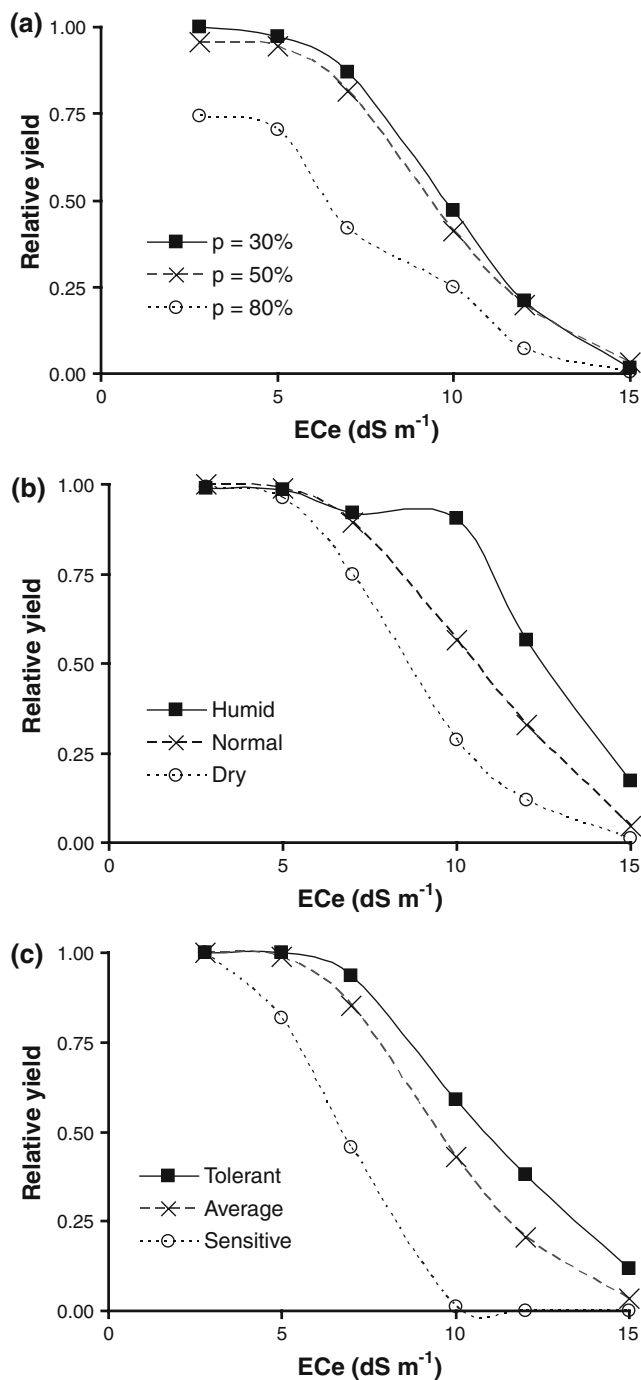
Fig. 2 Simulated relative yield response of common bean to soil salinity and **a** level of deficit irrigation, *p*, **b** *VPD* of the atmosphere and **c** crop salinity sensitivity

Fig. 3 Simulated relative crop water use in response of common bean to soil salinity and **a** level of deficit irrigation, **b** *VPD* of the atmosphere and **c** crop salinity sensitivity

The need for the second reduction factor acting on *SWFAC* is explained by considering case (a) in which different levels of deficit irrigation are employed. In the case with frequent irrigations (*P* = 30%), when soil water content does not limit transpiration, yield and water uptake are reduced at higher levels of soil salinity. Likewise, when
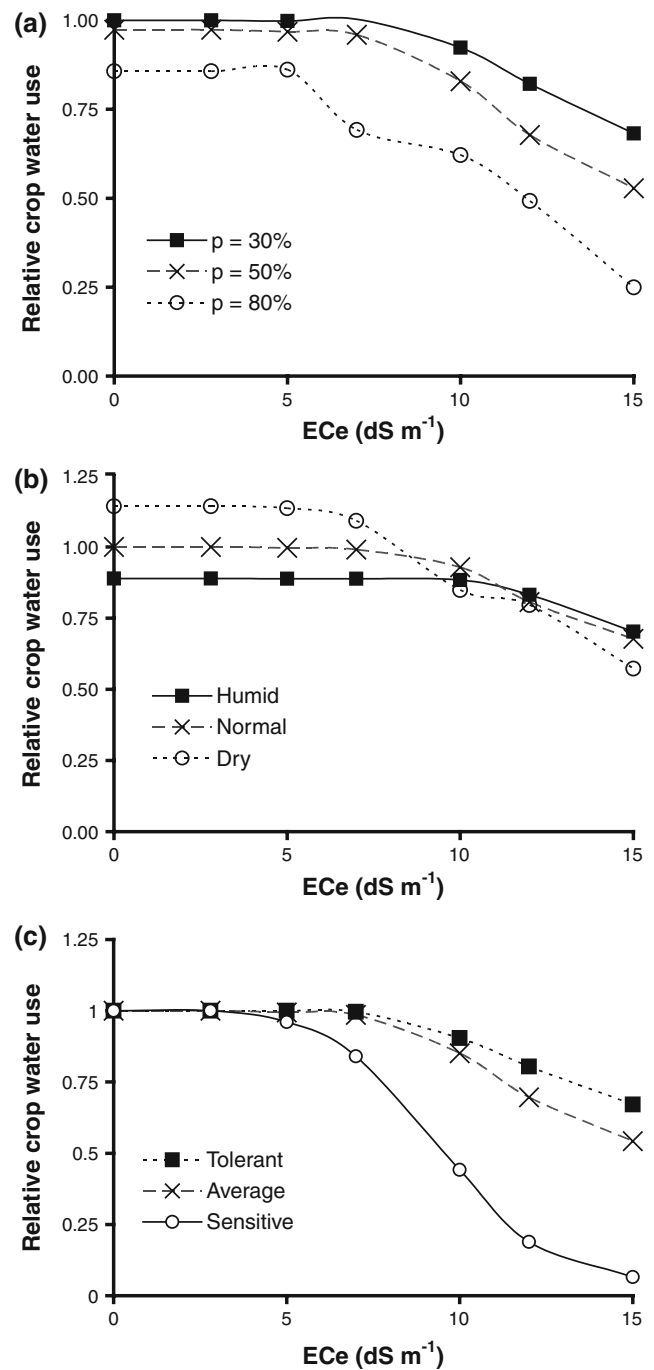
the irrigations were simulated less frequently, yield and water use were also reduced, though by greater amounts. This generally expected behaviour was only achieved in the model with the addition of the factor promoting stomatal closure. When this factor was not included, and the only effect of salinity was to reduce water uptake, the

Table 1 Soil fertility factor, soil salinity and cultivar parameters obtained during model calibration for the greenhouse dataset

Parameter	Value
Soil fertility factor (*SLPF*)	0.86
Rhizobia number (*ICRN*)	0
Rhizobia effectiveness (*ICRE*)	1
Soil salinity beyond which water use is depressed, ($EC_{threshold}$)	4.8 dS m^{-1}
Relative rate of reduction in water use due to salinity (*SALRDCT*)	4.6%/dS m^{-1}
S1	0.19
S2	1.08
Critical short day length below which reproductive development progresses with no day length effect (*CSDL*)	12.17 pd
Slope of response of development to photoperiod with time (*PPSEN*)	0.010 h^{-1}
Time between plant emergence and flower appearance (*EM-FL*)	24.0 pd
Time between first flower and first pod (*FL-SH*)	4.0 pd
Time between first flower and first seed (*FL-SD*)	13.5 pd
Time between first seed and physiological maturity (*SD-PM*)	24.0 d
Time between first flower and end of leaf expansion (*FL-LF*)	21.0 pd
Maximum leaf photosynthesis rate under optimal conditions (*LFMAX*)	1.00 mg CO_2 m^{-2} s^{-1}
Specific leaf area of cultivar under standard growth conditions (*SLAVR*)	0.032 cm^2 g^{-1}
Maximum size of full leaf (*SIZLF*)	0.015 cm^2
Maximum fraction of daily growth partitioned to seed and shell (*XFRT*)	1.00
Maximum weight per seed (*WTPSD*)	0.500 g
Seed filling duration for pod cohort at standard growth conditions (*SFDUR*)	11.0 pd
Average seed per pod under standard growing conditions (*SDPDV*)	4.00 pod^{-1}
Time for cultivar to reach final pod load (*PODUR*)	8.0 pd

pd photothermal days

simulations actually predicted increased yield with salinity if deficit irrigation was practised. This is explained by the effect of water uptake (and salinity) on leaf expansion rates. Under water stress, leaf area is reduced and the plant water loss is reduced, as a mechanism of drought avoidance. In CROPGRO, stomatal closure is simulated in the term *SWFAC*. This term was actually increasing with salinity and deficit irrigation, as the reductions in root water uptake were less than the reductions in potential transpiration (a function of leaf area).

Calibration and validation of cultivar and soil data

The cultivar traits obtained in the calibration routine were all within the range of values listed for other cultivars and are summarized together with the soil fertility factor, the rhizobia number and effectiveness factors and the parameters related to the new salinity response in Table 1. The measures of agreement for the cultivar calibration are listed in Table 2. The units of agreement all indicate a good initial calibration of the model for cultivar traits with no imposed salinity stress. The rhizobia number, which is a relative measure (ranging between 0 and 1) of the nodules present, was set to 0, indicating no nodules as no nodules were found in the soil bins. This was expected as the initial nitrogen levels were high and had no impact on the model

Table 2 Evaluation of the calibration (C) and the validation (V) of the cultivar traits for the greenhouse experiment using only treatments without salt stress

Variable of interest*	N**	Obs. mean	Sim. mean	RMSE	RE	MAE	*i*
Seasonal ET (mm)							
C	3	311	305	8.7	0.03	8	0.991
V	3	409	384	25.4	0.06	25	0.973
Final biomass (kg ha^{-1})							
C	3	4,469	4,335	276	0.06	181	0.989
V	3	6,713	4,018	2,806	0.42	2,695	0.590
Final yield (kg ha^{-1})							
C	3	903	898	37	0.04	31	0.998
V	3	1,386	1,450	130	0.09	123	0.993
Leaf area index							
C	3	3.95	3.58	0.4	0.10	0.37	0.919

* Note on units: Obs. mean, Sim. mean, RMSE and MAE have the same units as the variable of interest; RE and *i* are unitless

** *N* is the number of observations used in each simulation

performance. The rhizobia effectiveness is a relative measure (ranging between 0 and 1) of the effectiveness of the nodules present. This was set to 1, indicating full effectiveness, but as there were no nodules present, this had no effect on the model performance. The predicted above-

Table 3 Performance evaluation of the original and modified version of CROPGRO using the calibration (C) and the validation (V) greenhouse data sets

Variable of interest	Model version	N	Obs. mean	Sim. mean	RMSE	RE	MAE	i
Seasonal ET (mm)								
C	Original	9	299	298	11.4	0.04	10.54	0.986
	Modified	9	299	296	10.4	0.03	9	0.988
V	Original	9	379	366.1	19.5	0.05	17.2	0.987
	Modified	9	379	364	21.3	0.06	18	0.985
Final biomass (kg ha^{-1})								
C	Original	9	4,042	4,109	1,059	0.26	733	0.853
	Modified	9	4,042	3,875	957	0.24	633	0.886
V	Original	9	5,109	3,575	2,216	0.43	2,041	0.604
	Modified	9	5,109	3,569	2,231	0.44	2,071	0.601
Final yield (kg ha^{-1})								
C	Original	9	795	831	134	0.17	106	0.977
	Modified	9	795	800	108	0.14	85	0.983
V	Original	9	1,220	1,225	200	0.16	179	0.982
	Modified	9	1,220	1,262	212	0.17	187	0.979

ground biomass was considerably lower than the observed values during the validation simulations. The authors suspect the seasonal differences between the times of calibration (spring with shorter, increasing day lengths) and validation (summer with longer, decreasing day lengths), and the initial fair simulation results for leaf area are the cause of the poor biomass simulation. Further, biomass samples from four growth stages were used to calibrate the model to capture the general trend in increasing biomass over time not simply the final biomass values.

Calibration and validation of the new salinity response factor

Calibration of the salinity response function required adjustment of the four new parameters. The values obtained are given in Table 1. The values of $EC_{threshold}$ and *SALRDCT* (the relative reduction coefficient) did not need to be changed from the initial starting values obtained from extrapolation of the data on water use as a function of salinity obtained in the greenhouse trials (Webber et al. 2008). This was largely a result of the way the modified program was designed. The real calibration exercise was with the two parameters, S_1 and S_2, which control the degree of stomatal closure due only to salinity effects independent of water deficit. The fit was generally very good for both calibration and validation data sets as shown by the measures of agreement in Table 3 and Fig. 4. For comparison, the measures of agreement for the original model are also included. At first glance, the results are puzzling, and it may appear that the original model was

also responsive to salinity, as the two versions perform equally well. However, this is an artefact of the experimental design of Webber et al. (2008), which determined the response to soil salinity. In this experiment, all treatments with the same level of deficit irrigation were irrigated on the same day (i.e. no NaCl, depletion x; low NaCl, depletion x; and high NaCl, depletion x, where x is any one of the three levels of deficit irrigation). The day before irrigating, soil moisture was measured in all salt treatments (at that level of deficit irrigation) to determine the actual soil water content deficit and irrigations needed to return the treatment soil water content to field capacity. In almost all cases, the salt-treated plants used less water, and therefore needed smaller irrigation volumes to return their soil water content to field capacity. Therefore, the original model's apparent responsiveness to salinity is actually responsiveness to irrigation amount.

Field testing of the modified model

The results of the simulations of the Fergana Valley field experiments are shown in Table 4 and Fig. 5. The cultivar data calibrated in the greenhouse trial was used in these simulations, leaving only the soil fertility factor (*SLPF*) and the nodule number and effectiveness to be calibrated. This was performed with the treatments with no water stress (depletion 45%, conventional and alternate furrow irrigation). Individual plots were treated as individual observations, as significant block effects existed for soil type and planting date. The model agreement is considered fair for yield and water use. Model calibration was
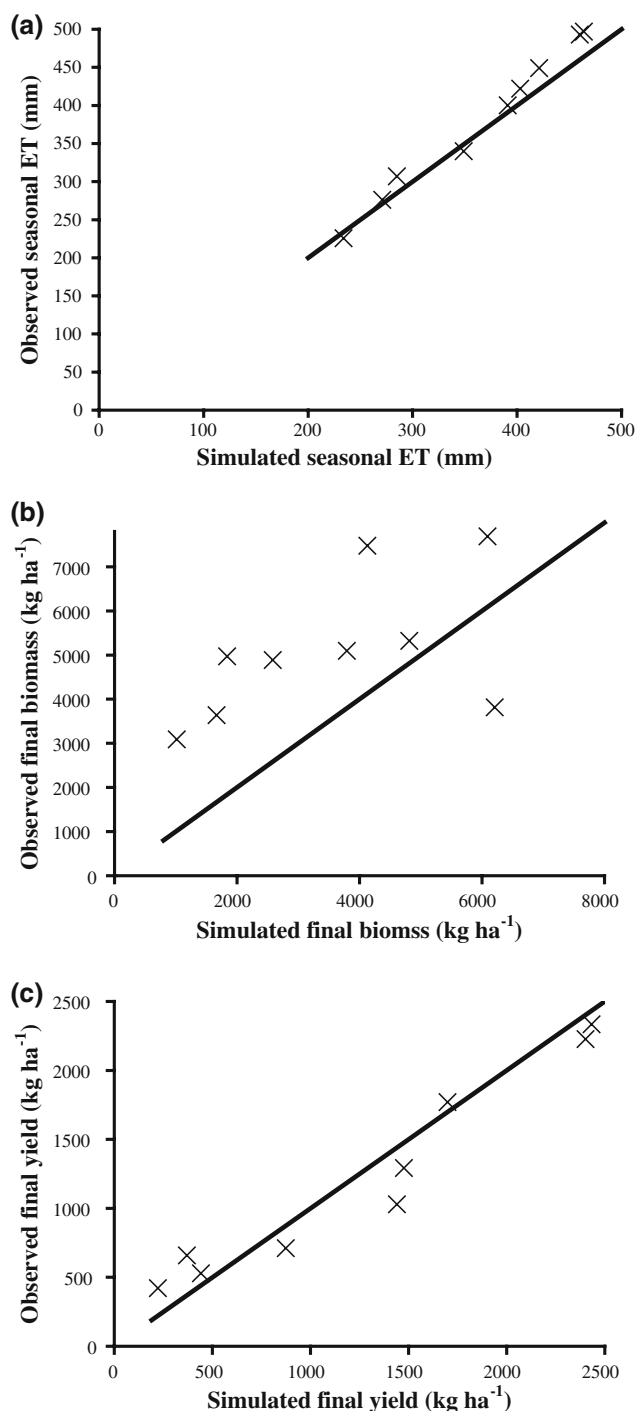
Fig. 4 Comparison of simulated and observed **a** seasonal water consumption, **b** final biomass and **c** final yield for the modified CROPGRO model. Data are from the validation set with three levels of deficit irrigation and three levels of soil salinity

Table 4 Performance indicators for the modified CROPGRO model applied to the field conditions of the Fergana Valley, Uzbekistan using three levels of deficit irrigation and conventional and alternate furrow irrigation

Variable of interest	N	Obs. mean	Sim. mean	RMSE	RE	MAE	i
Seasonal ET (mm)							
V	21	193	197	17.2	0.09	13	0.749
Final biomass (kg ha^{-1})							
V	21	1,984	3,438	1,680	0.85	1,488	0.259
Yield (kg ha^{-1})							
V	21	670	683	1,478	0.22	120	0.735

fertility factor, produced 6 and 8% increases in yield, whereas 20% increases in these values produced 10 and 15% increases in yield. By contrast, yield was much less sensitive to the two new parameters controlling the salinity stomatal response, S_1 and S_2. When S_1 was increased by 10 and 20%, yield increased by <1%. Yield decreased by 2 and 5% when S_2 was increased by these same amounts. This difficulty could be overcome by either (1) evaluating a crop that is well nodulated and assuming the nodule number was a maximum or (2) by testing the model with a non-nitrogen fixing crop to obtain a good estimate of the soil fertility factor.

Conclusions

The CROPGRO model was modified to be responsive to low to moderate soil salinity by adding an empirical root water uptake reduction function. The modified model was tested qualitatively and quantitatively for a common bean crop in soils where the dominant salt was gypsum. The qualitative analysis verified the model performed as expected for different levels of crop tolerance to salinity, levels of water vapour pressure deficit and irrigation frequencies. The model was able to correctly simulate yield and seasonal water use for a greenhouse experiment with three levels of soil salinity and three levels of deficit irrigation with a Willmott agreement index (i) of 0.98 for both variables. The modified model performed fairly well at simulating yield and seasonal water use for a field experiment conducted in the Fergana Valley of Uzbekistan (i of 0.75 for ET and 0.74 for final yield) with three levels of deficit irrigation, although simulation of final above-ground biomass was poor. Uncertainty in parameters related the rhizobia number and soil fertility factor for the field experiment, together with sample variability, make it difficult to evaluate the performance

complicated because of uncertainty in both the soil fertility and nodule number parameters. In a sensitivity analysis, 10% increases in the nodule number and the soil
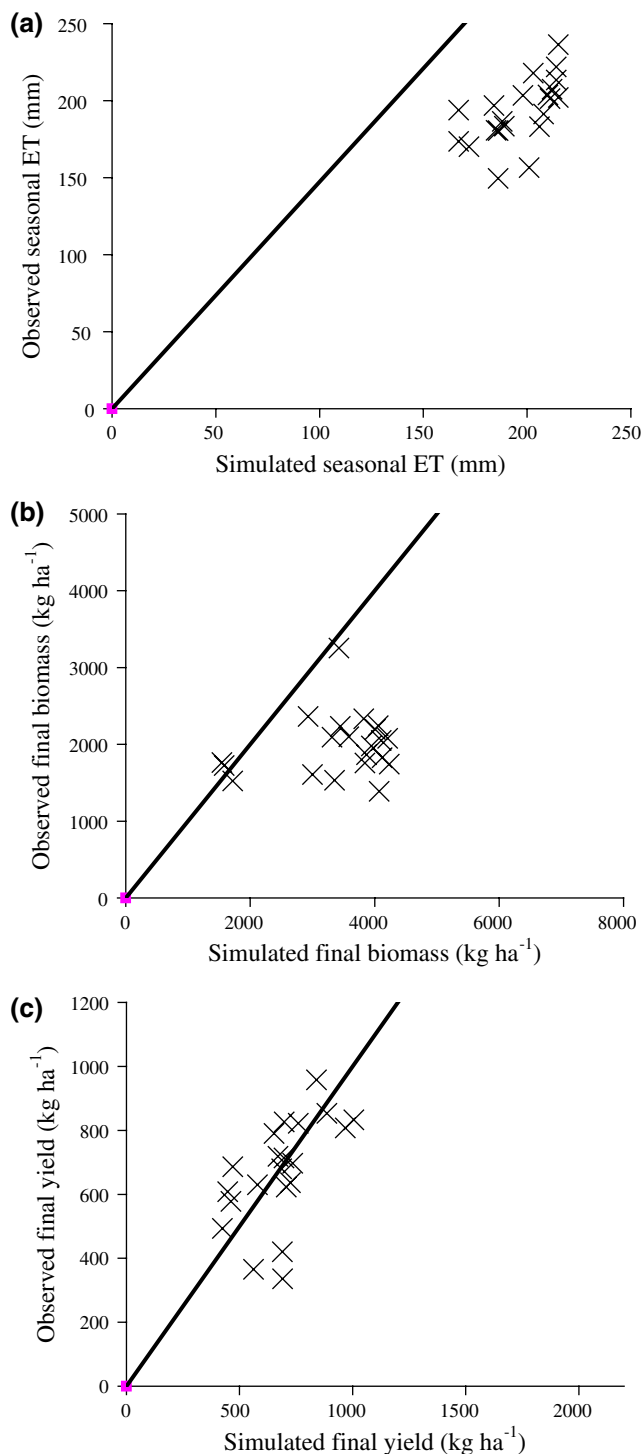
Fig. 5 Comparison of simulated and observed **a** seasonal water consumption, **b** final biomass and **c** final yield for the field experiment in Uzbekistan. Data are from three levels of deficit irrigation and alternate conventional furrow irrigation treatments

of the model. Future testing of the model should be conducted with a non-leguminous crop to avoid the complication associated with not knowing the rhizobia number and/or effectiveness.

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