

Drought and salinity tolerances of young *Jatropha***,**

H. Fujimaki* and N. Kikuchi

Graduate School of Life and Environmental Sciences, University of Tsukuba, Tsukuba, Japan

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A b s t r a c t. *Jatropha* (*Jatropha curcas* L.) is receiving attention recently as a biofuel crop. It has been introduced as drought resistant, but few quantitative data concerning its tolerance have been presented. We evaluated the tolerances of *Jatropha* to drought and salinity stresses in terms of parameter values in the widely used macroscopic root water uptake model. With such parameter values, root water uptake under stresses can be accurately predicted, which may contribute to efficient water management in arid and semiarid regions where irrigation is required to attain high yield. We conducted a column experiment using five columns with one plant each: three were under stresses, the others provided potential transpiration. Three TDR probes were inserted into each of the two columns to observe water content and electrical conductivity. The soil surface was covered to prevent evaporation. Weight of the columns was manually measured to obtain daily transpiration. After the stress period, root density distributions were obtained by dismantling the columns. Three parameter values were inversely determined by minimising the sum of square differences between observed and calculated daily transpiration rates. Water uptake at each depth and time was calculated by substituting linearly interpolated matric and osmotic potentials into the stress response function. Optimized daily transpiration rates agreed well with the observations. Determined stress response functions indicate that *Jatropha* is not more tolerant either to drought or to salinity compared to other major crop such as soybean or wheat.

K e y w o r d s: root water uptake, salinity stress, irrigation, bioenergy

INTRODUCTION

Jatropha curcas L. is a perennial shrub that produces oil-rich seeds and reported to have a high-yield potential (Openshaw, 2000; Ye *et al.*, 2009). It has received much

attention and has been planted over millions of ha in subtropical regions recently. The C3 plant has been stated to be drought tolerant (Achten *et al.*, 2008; Debnath and Bisen, 2008; Russell, 2009). However, few quantitative data for its tolerance have been published. Although it is stated that it can grow in marginal soils, 'marginal' yields are often reported from such land (Ye *et al.*, 2009). In addition to lower nutrient levels, drought stress in such lands may be attributed to low yield. This casts doubt on the tolerance of *Jatropha* to drought stress. Abdrabbo *et al.* (2009) evaluated oil yield at different irrigation levels. Such a report of relationship between irrigation level and yield may be useful but may not be applicable to other combinations of soil, climate, and salinity of irrigation water.

In drier regions, plantations irrigated with agricultural or municipal wastewater have been planned. For example, Egypt has already cultivated *Jatropha* using treated wastewater at more than 400 ha. Use of wastewater for biofuel production would be reasonable since municipal wastewater is generally not suitable for food production due to either potential health problems or psychological reasons, even after second treatment.

To optimize irrigation scheduling, drought and salinity tolerance must be known. Few studies on salinity tolerance of *Jatropha* have been performed. Gao *et al.* (2009) compared the biomass of seedlings of *Jatropha* at different NaCl solutions and reported that significant reduction in biomass occurred at higher than 0.1 M. It is still unclear whether their results can be applicable to older plants and fields where drought stress is often imposed simultaneously.

Since biomass production is proportional to transpiration amount, whether a plant can keep uptaking water from soil and thus transpiring under stress is the essence of tolerance. Commonly obtained relationships between treatments and yields in field or laboratory experiments do not

*Corresponding author's e-mail: fujimaki_haruyuki@yahoo.co.jp

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provide enough information how transpiration rate of a plant changes under given conditions. Therefore, root water uptake (RWU) models have been developed in efforts to predict plant response to irrigation and stresses (Feddes *et al.*, 1978; Nimah and Hanks, 1973). Macroscopic RWU models using stress response functions are widely employed in user-friendly simulation models of water and solute movement in soils, such as HYDRUS (Šimůnek *et al.*, 2006) and SWAP (van Dam *et al.*, 1997). Plant-specific parameter values in root water uptake models may be universal indices of the tolerance of plants to stress, since they do not depend on environmental conditions.

The purpose of this study was to determine *Jatropha* tolerance-related parameter values in a widely used root water uptake model. Then it was compared them with those of major crops.

THEORY

Transpiration rate, T_{cal} , is given by an integration of the rate of root water uptake, S (s^{-1}), over the root zone:

$$T_{cal} = \int_0^{\infty} S dz, \quad (1)$$

where z is depth (cm). Macroscopic models assume a potential root water uptake rate, S_p (s^{-1}), which is proportional to potential transpiration rate, T_p ($cm s^{-1}$), and root activity, β , which may be represented by root length density, ρ_r (cm^{-2}):

$$S_p = \beta T_p, \quad (2)$$

$$\beta = \frac{\rho_r}{\int_0^{\infty} \rho_r dz}. \quad (3)$$

Root water uptake rate is then given by a product of reduction coefficient, α and S_p :

$$S = \alpha S_p. \quad (4)$$

The reduction coefficient is a function of matric and osmotic potentials. This function is called the stress response function. Several variants differing in expressing combined water and salinity stress have been proposed (Feddes and Raats, 2004; Homae *et al.*, 2002). In this study, we employed one which is so-called additive form:

$$\alpha = \frac{1}{1 + \left(\frac{h}{h_{50}} + \frac{h}{h_{o50}} \right)^p}, \quad (5)$$

where: h and h_o are matric head and osmotic head, respectively, and h_{50} , h_{o50} , and p are fitting parameters (van Genuchten, 1987). Note that h_{50} and h_{o50} are potentials when water uptake is 50% of its potential rate and therefore represent simple indices of tolerance of crops. In this study, we determined these parameters, h_{50} , h_{o50} , and p of *Jatropha*.

MATERIALS AND METHODS

The columns having 29 cm in dia and 38 cm in height were placed in a greenhouse located in the Agricultural and Forestry Research Center, University of Tsukuba, Japan. To monitor water content and electrical conductivity (EC) in the soil, three TDR probes (CS630, Campbell Sci., Logan, UT, USA) were horizontally inserted into each of three columns (A, B, C), such that the depths of the middle rods were located at 5, 15 and 30 cm, respectively. Thermocouples were also inserted at the same depths as TDR probes to observe temperature. Two other columns (D, E) were used in the experiment as a control, but were not equipped with TDR or thermocouples. Hourly solar radiation was also recorded. Since the columns were not placed in the soil but above the ground, the columns were wrapped with glass wool of 5 cm in thickness to minimize temperature fluctuation and horizontal non-uniformity in temperature. Air-dry Kanto loam (Andisol, 50% of sand and 44% of silt) was packed to a bulk density of $0.84 g cm^{-3}$. Such a low bulk density even after light compaction is a remarkable character of the volcanic ash soil.

Seeds of *Jatropha* obtained from Thailand were sown on June 12, 2008, and each one was transplanted into the column on June 29. The stress period started after healthy plants had grown by irrigating sufficient amount of tap water ($EC = 0.6 dS m^{-1}$) with 3,000 fold-diluted liquid fertilizer.

Irrigation with NaCl solution started at sunset on September 6, 2009. During the salinity stress period, irrigation amounts were determined for each column to replenish the loss by transpiration since the previous irrigation. In such a scheme, salt gradually accumulates in the root zone while avoiding drought stress. By gradually increasing the salinity as such, we can observe the response of transpiration across a wide range of salinity. The daily transpiration rate was measured by manually weighing the columns at sunset. The soil surface was covered with a white-coloured, 1 cm thick styrene foam to prevent evaporation from the soil, thus isolating transpiration. The NaCl concentration of applied water was $2,000 mg l^{-1}$. The other two columns and plants were used to provide potential transpiration by continuing irrigation with sufficient amount of tap water. The last irrigation was applied on October 2, 2009. The experiment was terminated on October 12, when the relative transpiration, the ratio of actual to potential transpiration, became about a quarter.

After the stress period, the columns were dismantled to obtain root length density distribution. Soil and root samples at each 5 cm layer were air-dried and sieved with 0.8 mm screen. Then the air-dry roots were scanned with a flatbed scanner with 600 dpi. Total length of root in an image was determined with the intersection method.

We followed the method proposed by Fujimaki *et al.* (2008) in the data analysis. Parameter values in the response function, h_{50} , h_{o50} and p , were inversely estimated such that

the sum of squares between calculated and measured daily transpiration rates is minimised. Daily transpiration was calculated by integrating hourly-calculated transpiration rates, T_{cal} (cm s^{-1}), during the daytime. At a given combination of h_{50} , h_{o50} and p , transpiration rate at each time was calculated using Eqs (1-5). The procedure for estimating the potential transpiration rate, T_p , was slightly different from the one by Fujimaki *et al.* (2008) and will be discussed later. Equation (5) requires h and h_o at each depth. We determined a calibration equation to convert the dielectric permittivity measurement using TDR to volumetric water content, θ , for Kanto loam. Profiles of θ were obtained by linearly interpolating and extrapolating the values at the depth of TDR measurement. We estimated matric head at each time and depth from water retention curve of the soil. Since water content of the whole profile did not necessarily reach saturation, we considered hysteresis in the conversion using a simple method by Kool and Parker (1987). The use of polymer tensiometers (de Rooij *et al.*, 2009) may allow direct measurement of very low matric head, which usually occurs in drought stress experiment.

We also obtained the dependence of bulk EC, σ_b , on θ , which is required to calculate the EC of the soil solution, σ_w , from σ_b and θ measured with TDR. Using another calibration equation, observed σ_b was converted to that of soil solution, σ_w . Because σ_w also depends on temperature, it was normalized to that at a reference temperature. We estimated the profile of σ_w by linearly interpolating and extrapolating the values at the depth of TDR measurement. The values of σ_w were converted to salt concentration, C (mol kg^{-1}), assuming that NaCl is the only solute. The osmotic potential, h_o (cm), of the solution can be estimated from (Fujimaki *et al.*, 2008):

$$h_o = \omega \nu C \chi R T, \quad (6)$$

where: ω is a unit-conversion factor ($10.2 \text{ cm kg J}^{-1}$), ν is the number of ions per molecule, χ is the osmotic coefficient, which was assumed to be unity, R is the universal gas constant ($8.31 \text{ J mol}^{-1}\text{K}^{-1}$) and T is temperature.

RESULTS AND DISCUSSION

Figure 1 shows time evolution of leaf area. There was a large variation in growth. In the initial preparatory stage, we did not determine irrigation depths to meet evapotranspiration loss and this may have led to a slight drought stress (column C) or over-irrigation (column D), since growth of column C was so slow that we could not impose drought stress due to low transpiration rate. Unlike annual crops, tree crops keep growing even during the stress period. Also, the ratio of leaf area changed with time. In this case, we cannot assume that the ratio of potential transpiration among plants is constant as done in Fujimaki *et al.* (2008). We found that under stress-free conditions, daily transpiration rates were proportional to leaf area. We thus estimated the potential transpiration of stressed plant by multiplying daily transpiration amount of controls with the ratio of leaf area. Potential transpiration rates at every hour were estimated by assuming that the pattern of transpiration was the same as that of solar radiation.

Shown in Fig. 2 is the time evolution of relative transpiration, which is the daily transpiration amount of stressed plant over that of control, and daily potential transpiration rate of column A. In response to depletion of water and irrigation with saline water, relative transpiration gradually decreased. The decrease was more rapid for plant B, since B had about twice the transpiration of A. Daily potential transpiration largely fluctuated in response to climatic conditions. Relative transpiration tended to recover when potential transpiration was low. This tendency, relaxations under

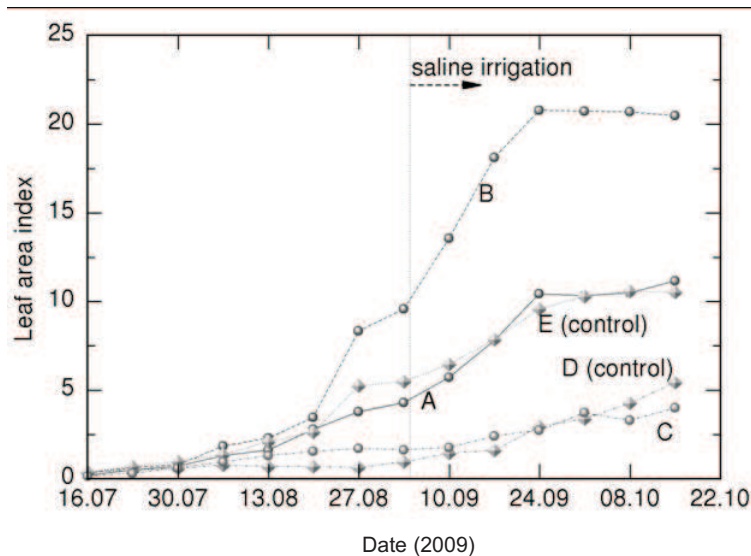


Fig. 1. Time evolution of leaf area index. A, B, C, D, and E – represent the columns with the growing each plant.

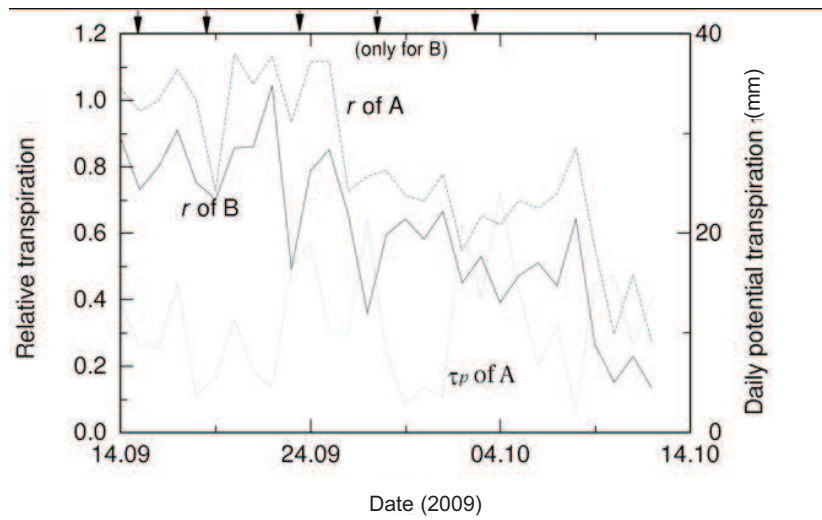


Fig. 2. Time evolution of relative transpiration and daily potential transpiration of column A and B. Arrows indicate when saline water was applied.

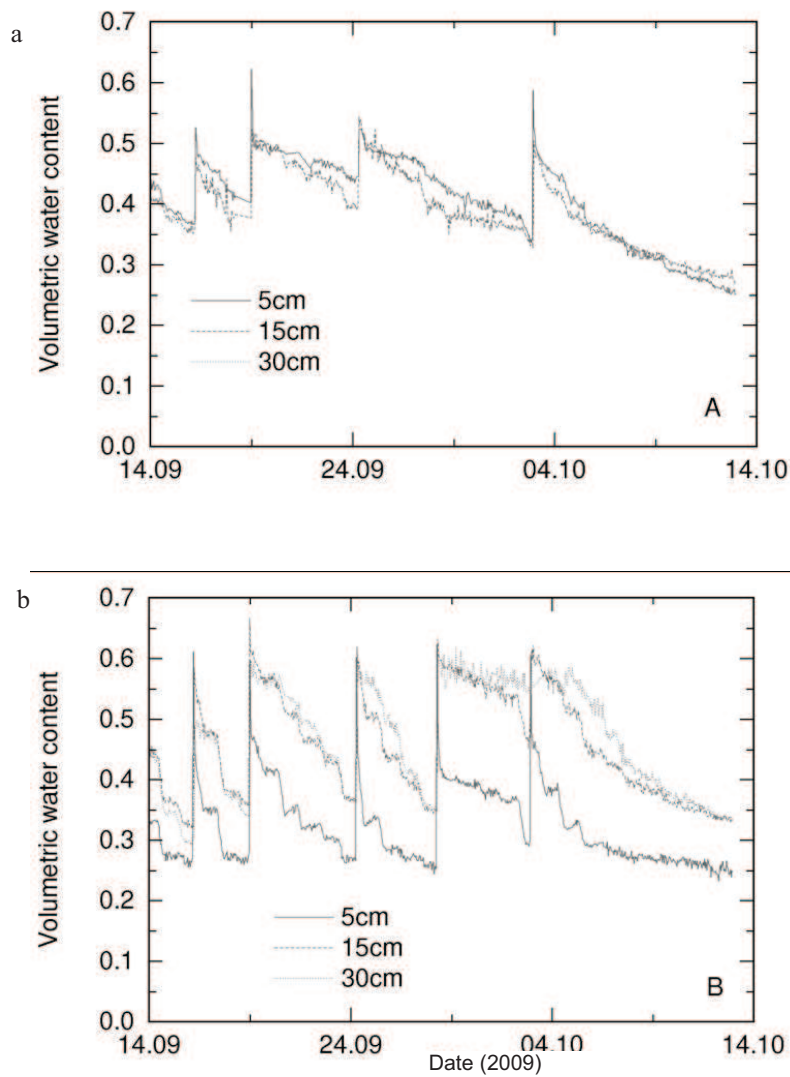


Fig. 3. Time evolution of water content: a – column A, b – column B.

low evaporative demand, has been commonly reported and theoretically explained with the soil-plant-atmosphere-continuum (Feddes and Raats, 2004; Hillel, 1998).

Figures 3 and 4 show the water content and electrical conductivity of soil solution, σ_w , respectively. Regarding to column A, while water content was relatively uniform, σ_w at the depth of 15 cm was higher than at the upper and lower depths. In the final period, both drought and salinity stress were imposed. For column B, water content in the upper layer depleted quickly due to higher transpiration and it seems that accumulated salts were transported into lower layers. Retention curve for Kanto loam used to estimate matric head from water content is shown in Fig. 5. An example of hysteresis trajectory for the top of column A is also plotted.

Shown in Fig. 6 are the profiles of root length density. Figure 7 shows an example of the profile of the product of reduction coefficient, α , and root activity, β , at the noon of October 12 when the plant suffered severe stresses. Although

β near the soil surface was far larger than that near the bottom, $\alpha\beta$ (at optimized parameter) near the surface was comparable to that near the bottom since both were low in the surface layer.

Figure 8 compares measured and calculated transpiration ratio at the minimum RMSE for column A. Large discrepancy occurred when potential transpiration was very low. Except for such data, the accuracy is acceptable.

Figure 9 shows optimized stress response functions. Drought stress response function is drawn by setting osmotic head at zero. Similarly, a salinity stress response function is drawn by setting matric head at zero. Data for maize, potato and wheat were obtained from tables by van Dam *et al.* (1997).

It indicates that *Jatropha* is less tolerant to drought stress than maize. This corresponds to results obtained by Gerbens-Leenesa *et al.* (2009) who reported that the amount of water required to produce unit energy for *Jatropha* was far larger than for maize. *Jatropha* may survive under drought owing

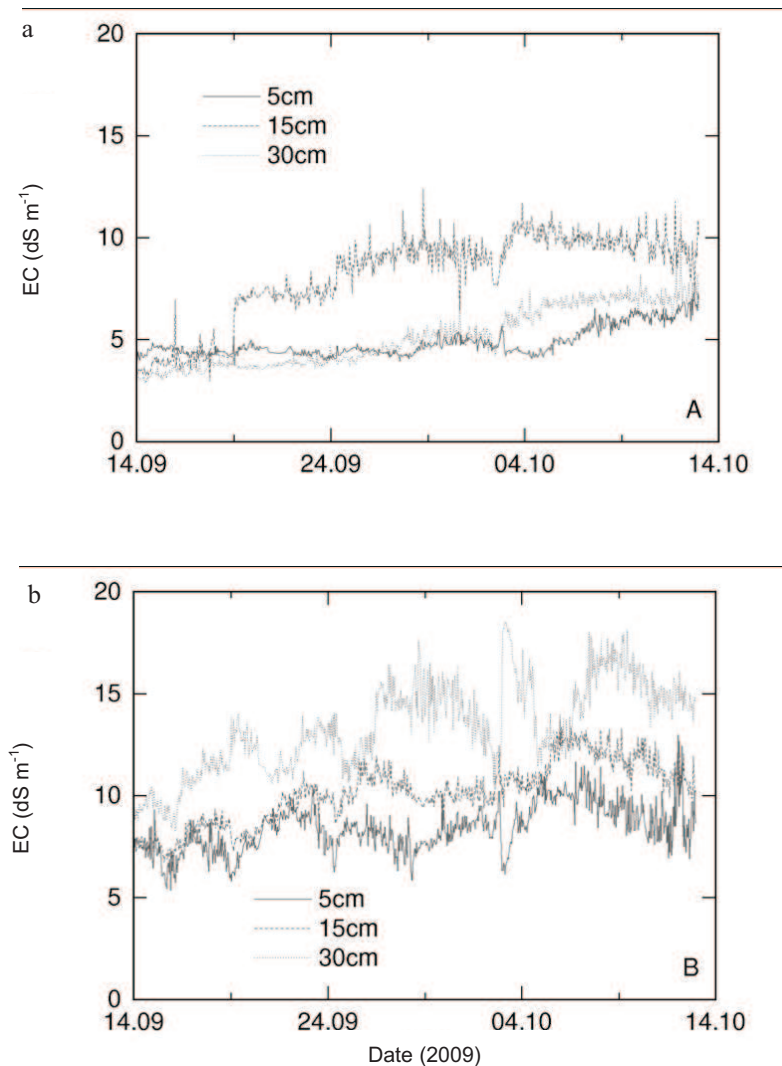


Fig. 4. Time evolution of electrical conductivity (EC) of soil solution: a – column A, b – column B.

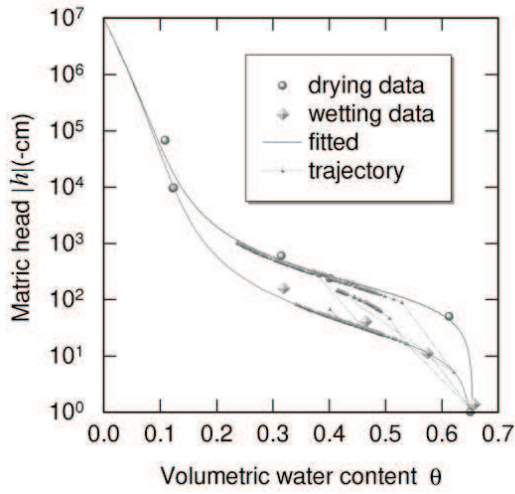


Fig. 5. Soil water retention curves for the Kanto loam.

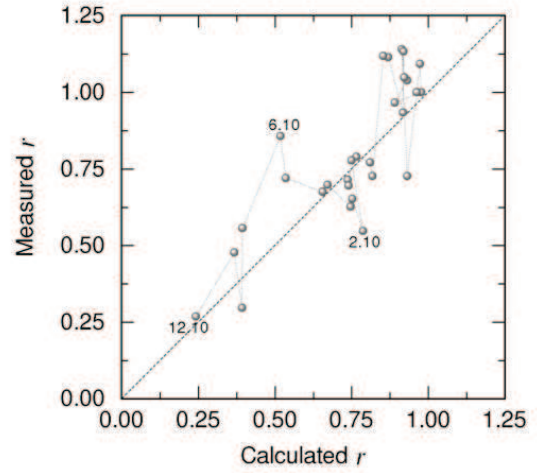


Fig. 8. Comparison of measured and calculated ratio of actual to potential daily transpiration (r) (column A).

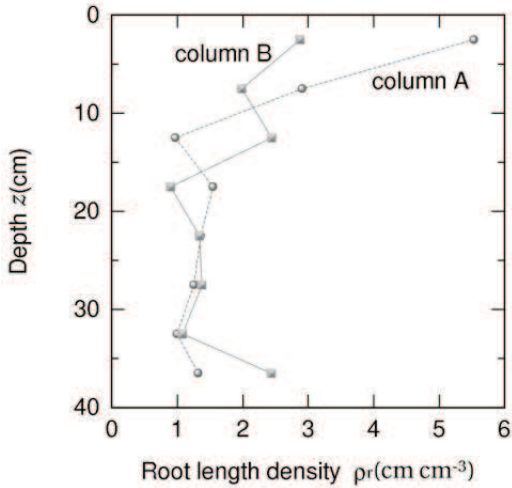


Fig. 6. Profiles of root length density.

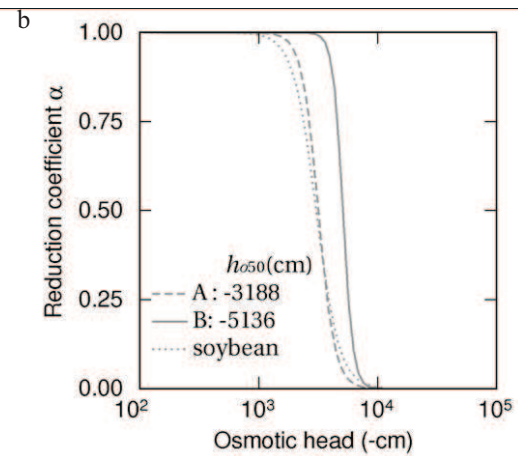
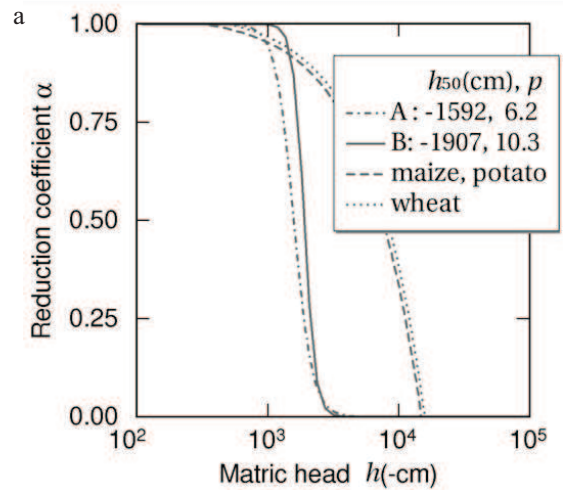


Fig. 9. Stress response functions for *Jatropha*, a – data for maize, potato and wheat were obtained from tables by van Dam *et al.* (1997); b – data for soybean were obtained from Fujimaki *et al.* (2008).

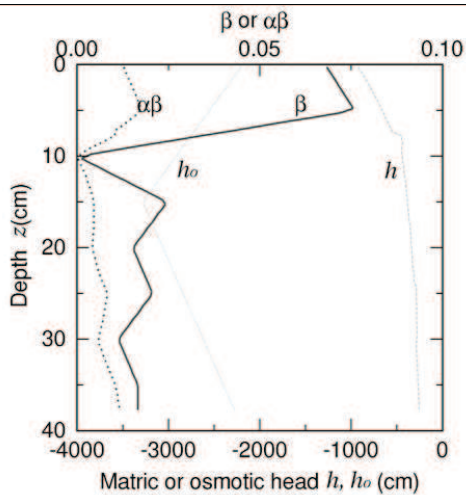


Fig. 7. Examples of the profiles on October 12 at 12:00 (column A), ρ – root activity; α – reduction coefficient.

to its relatively deep root zone compared to annual crops, but it does not necessarily mean that *Jatropha* can keep growing and producing seeds during drought.

On the other hand, salinity stress response function of *Jatropha* is comparable with that of soybean, which is a moderately tolerant crop. The absolute values of h_{o50} were about twice as high as h_{50} : *ie* at a given potential, matric potential was more effective than osmotic potential for root water uptake by *Jatropha*. This tendency is commonly found in various crops (Feddes and Raats, 2004). This may indicate that plasma membrane of root is not an ideal semi-permeable membrane but some ions may intrude into cells, which may reduce the difference in inner and outer osmotic potentials.

CONCLUSIONS

1. Determination of plant-specific parameter values in widely used root water uptake model for young *Jatropha* indicated that it is not more drought tolerant as compared to major crops.

2. As for salinity stress, it appeared to be moderately tolerant.

3. Since variations in growth and parameter values were large, further experiments may be needed to reach more solid conclusions.

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