

MODELLING OF WATER POTENTIAL AND WATER UPTAKE RATE OF TOMATO PLANTS IN THE GREENHOUSE: PRELIMINARY RESULTS.

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Abstract

A dynamic model is presented which predicts water potential and water uptake rate of greenhouse tomato plants using transpiration rate as input. The model assumes that water uptake is the resultant of water potential and hydraulic resistance, and that water potential is linearly related to water content of the plant. A comparison of measured and predicted values shows a reasonable correspondence. Values used for the coefficients of the model are $0.9 \text{ bar g min}^{-1}$ for root resistance, 3 bar g min^{-1} for whole plant resistance and $4 \times 10^{-3} \text{ g g}^{-1} \text{ bar}^{-1}$ for capacitance. A sensitivity analysis shows that for tomato an accurate determination of resistances is more important than an accurate determination of capacitance.

Models like this can be incorporated in crop growth models. They may contribute to the optimization of plant growth through control of transpiration rate and control of the root zone climate in soilless culture.

1. Introduction

Dynamic simulation models are being developed which predict dry matter production of a greenhouse crop as a result of climatic conditions in the greenhouse (Challa, 1985). Also models which simulate transpiration from a greenhouse canopy have become available (Stanghellini, 1987). Transpiration is not only important for climate control in the greenhouse (the greenhouse climate will be influenced by transpiration, and irrigation can be scheduled according to transpiration) but it also has an influence on water potential of the plant. Water potential has an influence on stomatal resistance and leaf expansion (Hsiao, 1973). In this way transpiration is related to dry matter production.

A model describing the effects of transpiration and other factors on water potential, and describing the effect of water potential on dry matter production could be incorporated in crop growth models. Thus such a model could serve as a tool in the optimization of plant growth through a control of transpiration rate and other factors. Among these other factors which influence water potential, the nutrient concentration (osmotic potential) in the nutrient solution seems to be an important one (Bruggink, 1987).

Research on the modelling of the internal water status of plants has been carried out extensively with fruit trees (e.g. Landsberg, 1976; Powell and Thorpe, 1977). The purpose of this paper is to present a preliminary model for the internal water status of tomato which is

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based on the mentioned work, although some simplifications were made. The behaviour of the model is investigated and the predictions of the model are compared with experimental data.

2. Model description

In the present model measured transpiration is used as a forcing function, but it could be replaced by simulated transpiration in an extended version of the model. In order to keep the model as simple as possible only the following assumptions were made:

- (1) Water uptake can be described via a resistance analogon (van den Honert, 1948):

$$U_1 = - (\text{PSI}_{\text{stem}} - \text{PSI}_{\text{solution}}) / R_{\text{root}} \quad (1)$$

$$U_2 = - (\text{PSI}_{\text{leaf}} - \text{PSI}_{\text{stem}}) / R_{\text{leaf}} \quad (2)$$

In which U_1 = water transport (gr min^{-1}) from the solution to roots and stem, U_2 = water transport from roots and stem to the leaves, PSI = water potential (bar) and R = resistance (bar min g^{-1}). The distinction between the water potential of nutrient solution, leaves and roots plus stem is made because of the relatively large hydraulic resistances located in the roots and between the stem xylem and the transpiration sites inside the leaves (Boyer, 1985).

- (2) Water potential of a plant part is linearly related to water content of a plant part (Landsberg et al., 1976):

$$\text{PSI} = - (1 - W/W_{\text{max}}) / C \quad (3)$$

In which W = fresh weight, W_{max} = fresh weight at $\text{PSI}=0$ and C = capacitance ($\text{g g}^{-1} \text{bar}^{-1}$).

The first assumption is sufficient to describe PSI under steady state conditions (when uptake equals transpiration). The second assumption is necessary to describe the dynamic behaviour of PSI and water uptake.

The relationships between eqn 1, 2 and 3 are shown in figure 1. This relational diagram was implemented in a computer program, which calculates PSI and water uptake over 1 minute intervals, using transpiration as input.

Resistances were determined experimentally. For capacitance a value of $4 \times 10^{-3} \text{ g g}^{-1} \text{bar}^{-1}$ was chosen, based on measurements by Landsberg et al. (1976) on young apple trees. For W_{max} measured values of plant fresh weight were used although it should be noticed that these were determined at the end of the growing season and therefore can only be approximations. Weight of fruits was not included in W and W_{max} because fruits show little variation in diameter (and thus fresh weight) over the day (J.C. Bakker, personal communication) in contrast to stems which show strong diameter changes over the day (data not shown).

3. Material and methods

The experimentally obtained data were collected in a greenhouse where tomato plants (cv. Turbo) were growing in rockwool with drip irrigation at a density of 2 plants per m^2 .

Climate control and cultural practices were according to standard practice for a tomato crop, but electrical conductivity (EC) of the nutrient solution was somewhat higher than normal: 5 and occasionally upto 10mS.

Measurements were carried out from the end of April till the middle of June, during that period the plants had, due to regular removal of fruits and leaves, a fairly constant size. Plant size at the end of June is listed in Table 1.

Transpiration was calculated from the weight loss of four plants, placed on an electronic weighing device (Stanghellini, 1987). Water uptake was measured on a comparable plant which was placed with its roots in a potometer (Bruggink, in preparation), due to the method of measurement no continuous data on water uptake are available. Both values were calculated over 5 or 10 minute intervals. Temperature, relative humidity and incoming global radiation were measured and recorded together with the above mentioned signals.

On four days water potentials of leaves and stems were measured destructively by means of a pressure chamber on plants randomly distributed over the greenhouse, as described by Hopmans et al. (1985).

Hydraulic resistances of the root and the whole plant were calculated from the relationship between transpiration and water potential of stem or leaves. This resulted in values of $0.9 \text{ bar min g}^{-1}$ for the roots and $3.0 \text{ bar min g}^{-1}$ for the whole plant. If we assume that the major resistances are located in the roots and the leaves, this means a leaf resistance of $2.1 \text{ bar min g}^{-1}$. When transpiration was zero PSI_{leaf} was 3.6 bar and PSI_{stem} 2.8 bar.

3. Results

3.1 Measurements of transpiration and uptake of water

Figure 2 shows an example of measured transpiration and water uptake on May 15. Transpiration as well as water uptake show a strong fluctuation which is closely related to the amount of incoming radiation (data not shown). Uptake follows transpiration with a delay of 10 to 15 minutes.

On average water uptake was about 10% higher than transpiration. Because this is more than the daily increase in fresh weight of the plants, this difference was assumed to arise from differences in plant size or location in the greenhouse. Water uptake was therefore corrected by multiplication with a factor 0.9. Even then a relatively large difference between transpiration and uptake remains at night, this possibly reflects an increase in fresh weight of the plant.

3.2 Simulation of water potential and water uptake

Simulation runs were carried out with the previously mentioned coefficient values. The simulated daily course of PSI_{leaf} for June 14 is compared to measured values (figure 3). Because this was a cloudless day with only gradual changes in transpiration, water uptake and PSI_{leaf} , only the level and not the dynamics of the course of PSI_{leaf} can be checked.

No data on PSI_{leaf} are available for a day with more fluctuating conditions, therefore, to check the dynamic behaviour of the model, the predictions are compared to data for water uptake (which, according

to eqn 1 and 2 is closely related to water potential) for May 15 (figure 4).

For PSI_{leaf} on June 14 as well as for water uptake on May 15 there is a good agreement between simulated and measured values.

3.3 Sensitivity analysis

From the description of the model a large sensitivity of the level of water potential to the value of resistance can be anticipated whereas the dynamics will be mainly sensitive to the value of capacitance. Figures 5 and 6 show that this is indeed true, although the sensitivity to capacitance is small compared to that to resistance. Equation 3 shows that the sensitivity of the model for plant size is similar to that for capacitance, and thus small.

4. Discussion

4.1 Model description

The present model fairly well describes the level of water potential and the dynamics of water uptake and thus probably also the dynamics of water potential. However, some important and well established aspects of water relations were not included in the model. The consequences of this will be discussed.

At low water uptake rates often a change in root resistance appears. This phenomenon is caused by the active uptake of nutrients which leads to uptake of water. A quantification of this process was given by Dalton et al. (1975) and Fiscus (1975). From their analysis it follows that this active uptake is mainly important at low transpiration rates. For this model, which describes a spring and summer situation with relatively large transpiration rates, it is therefore of little consequence. However, in a winter situation this aspect should probably be included.

An implicit assumption in our model is that PSI will be equal throughout the plant part considered. In reality gradients will exist within a plant part, especially after a change in transpiration rate (Boyer, 1985). This can be seen from the gradual decrease in weight or size of a plant part after a sudden change in xylem water potential. Relaxation times determined for this change in weight or size have been determined as 1.2 min for apple leaves (Powell and Thorpe, 1977), from 50 to 230 min for apple trunks (Landsberg et al., 1976; Powell and Thorpe, 1977) and 40 min for cotton stems (Molz et al., 1973). Preliminary measurements of changes in stem diameter after a sudden change in xylem PSI , which we carried out on tomato, gave values of around 10 min for the relaxation time. It thus seems that in the case of tomato this additional dynamic behaviour of the plant is of little consequence.

4.2 Measurement of coefficient values

The values we determined for hydraulic resistance of the whole plant (when expressed per unit leaf area) can be compared to values collected by Kaufmann (1976), our values fall within the wide range mentioned. The fact that root resistance is only about one third of total resistance is somewhat surprising, but a similar result was obtained by Davies and Lakso (1979) for young apple trees. The sensitivity analysis showed that the predicted water potential is

very sensitive to the values chosen for resistances. Therefore a more accurate determination of these resistances seems necessary as well as more knowledge of their dependence on other climatic factors. The sensitivity to the value chosen for capacitance is relatively small and its doubtful if the model can be improved by a more accurate determination of this value.

5. Conclusion

The present preliminary model gives a reasonable prediction of level and dynamics of water potential. In order to incorporate the model into crop growth models some refinement seems necessary as well as more knowledge about the magnitude of hydraulic resistances. Besides, additional information is needed about the relationships between water potential, dry matter production and developmental processes in the plant.

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Table 1 - Dry weight, fresh weight and leaf area of the plants used in the experiments. Plants were measured at the end of June. Size of the above ground parts is the average of the four plants used for transpiration measurements. Root weight was determined on the plant used in the potometer

	fresh weight (g)	dry weight (g)	leaf area (cm ²)
leaves	384	59	7000
stem	563	88	
roots	288	18	
fruits	470	40	

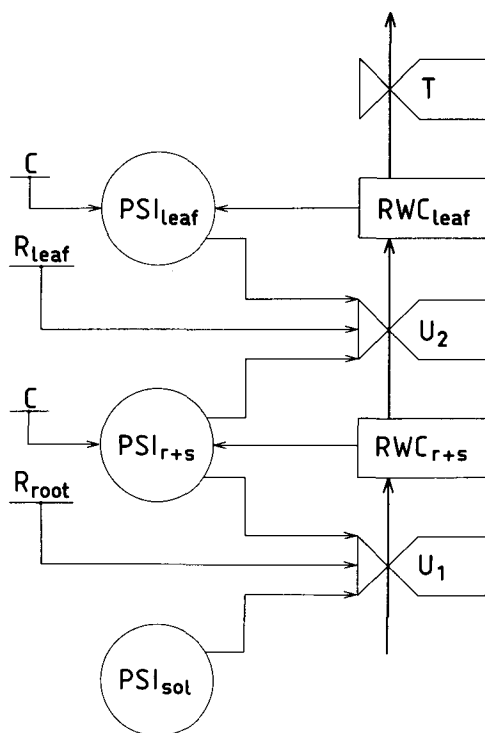


Figure 1. Diagram relating transpiration (T), relative water content (RWC), capacitance (C), water potential (PSI), hydraulic resistance (R) and water uptake (U₁ and U₂) for leaves, root and stem (r+s) and nutrient solution (sol).

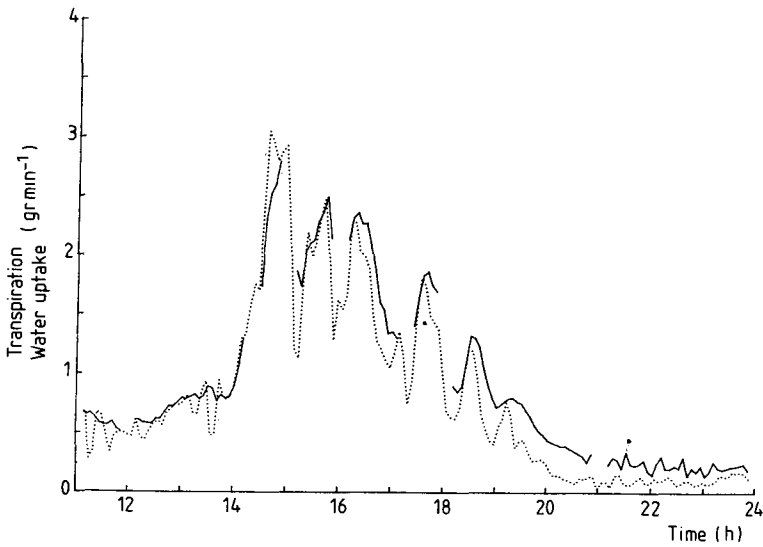


Figure 2. Daily course of transpiration (dotted line) and water uptake (drawn line) of tomato plants in the greenhouse (May 15, 1986). Both values in gr min^{-1} per plant.

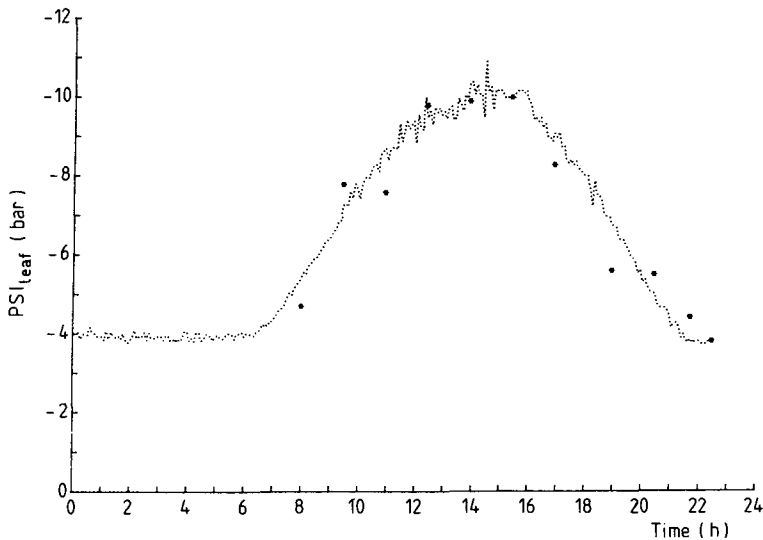


Figure 3. Measured (data points) and simulated (dotted line) daily course of PSI_{leaf} (bar) of tomato plants in the greenhouse (June 14, 1986).

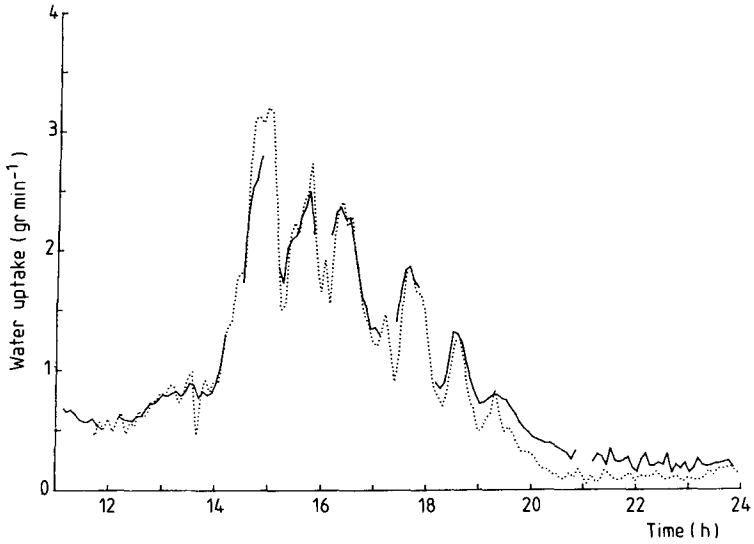


Figure 4. Measured (drawn line) and simulated (dotted line) daily course of water uptake (gr min^{-1}) of tomato plants in the greenhouse (May 15, 1986).

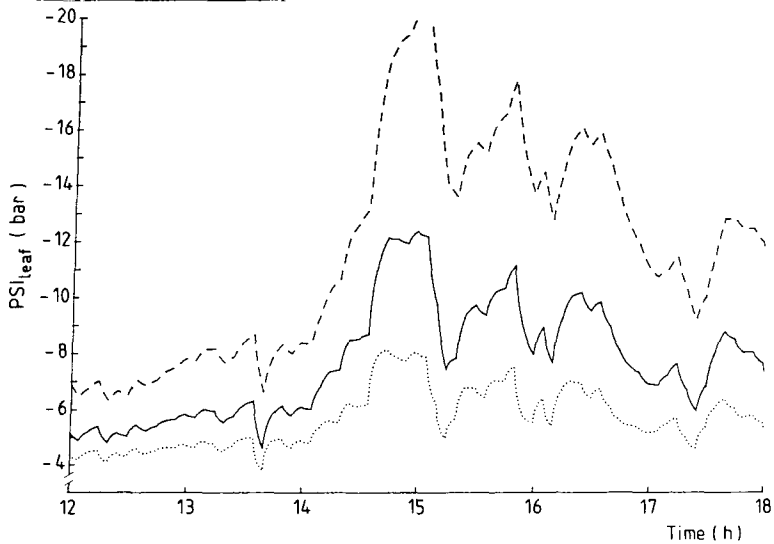


Figure 5. Simulated PSI_{leaf} of tomato plants using different values for resistance of root and whole plant.

drawn line: $R_{\text{root}} = .9 \text{ bar min g}^{-1}$; $R_{\text{plant}} = 3.0 \text{ bar min g}^{-1}$
dotted line: $R_{\text{root}} = .45 \text{ bar min g}^{-1}$; $R_{\text{plant}} = 1.5 \text{ bar min g}^{-1}$
broken line: $R_{\text{root}} = 1.8 \text{ bar min g}^{-1}$; $R_{\text{plant}} = 6.0 \text{ bar min g}^{-1}$
In all cases $C = 4 \times 10^{-3} \text{ g g}^{-1} \text{ bar}^{-1}$.

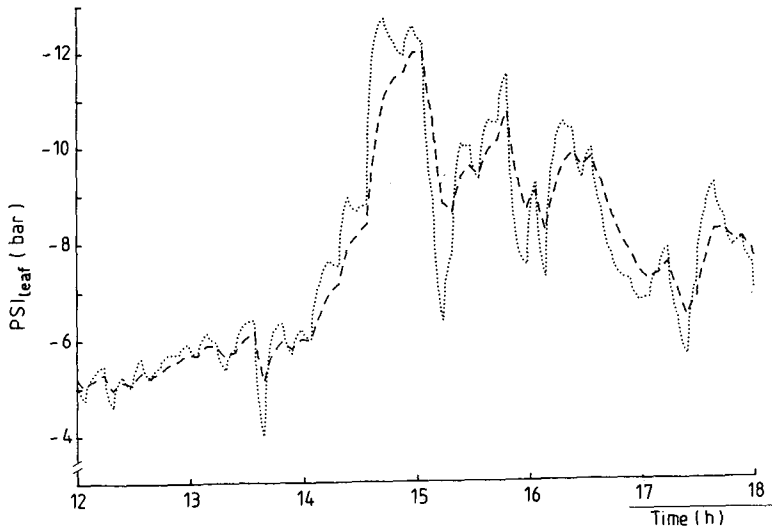


Figure 6. Simulated PSI_{leaf} of tomato plants using different values for capacitance.

dotted line: $C=2 \times 10^{-3} \text{ g g}^{-1} \text{ bar}^{-1}$

broken line: $C=8 \times 10^{-3} \text{ g g}^{-1} \text{ bar}^{-1}$

In both cases $R_{root} = .9 \text{ bar min g}^{-1}$ and $R_{plant} = 3.0 \text{ bar min g}^{-1}$.