שילוב שיטות בקרה קרקעיות, צמחיות ואקלימיות ליעול ה | 306-0286-97

תקציר הדו"ח:

מטרת המחקר הייתה להגדיר קריטריונים להשקייה המבוססים על יכולת בית השורשים לקלוט מים שקצב צריכתם ע"י הצמחים מבוקר ע"י הדרישה האטמוספרית להתאדות וע"י תגובות הצמח לתנאי עקת מים. בנוסף לצד המדעי תיאורטי, המחקר בחנה כלים ושיטות לניטור מצב מים בצמח ובקרקע ואומדן היקף הנוף כדי ליישמם באופן מעשי בבקרת השקייה בשדה. המטרה לטווח ארוך של המחקר היא לבנות מודל תפעולי שיספק המלצות להשקייה על בסיס אזורי לאורך עונת ההשקייה. ואכן, כתוצאה מהמחקר, המודל במידה רבה קיים.

הצד הניסויי של המחקר התרכז בניסויי שדה במרכז הארץ בשנות 1996,1995 ו- 1997. הניסויים היו בשדות תירס ששימשו כמודל לבחינת התפלגותהמים ומעברו במערכת קרקע, צמח ואטמוספירה. הניסויים נעשו בקרקעות הכבדות ווריאביליות של בית דגן ובקרקעות הקלות-חוליות של רחובות. נמדדו השתנות בזמן ובמרחב של התפלגות מים ושורשים בקרקע, התאדות מהקרקע, מעבר מים בנבעול, מצב המים בצמח, התנגדות עלים למעבר אדי מים, מבנה וטמפרטורת הנוף, ותנאים מטאורולוגים.

משטר ההשקייה בניסויים המאוחרים (לאחר לימוד המערכת), דהיינו בשנה השניה והשלישית של המחקר, נקבעה באופן הבא: עיתוי ההשקייה לפי סף של היחס בין צריכת מים של הצמח בפועל (מדודה) חלקי צריכת מים תיאורטי של אותו צמח בעלת עלים רטובים (דיות פוטנציאלית) לפי הנתונים המטאורולוגים. כמויות השקייה לפי מודל של דיות של אותו צמח בתנאים אופטימליים.

התוצאות העיקריות של הניסוי הם:

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נאסף מידע רב על ההתפלגות של מים ושורשים בקרקע. עיבוד מידע זה טרם הסתיים, אבל בינתיים נמצא שקיימת התאמה טובה בין צריכת המים המדודה לבין קצב ריקון הקרקע ממים.

חוקר ראשי: יתצחק כהן מינהל המחקר החקלאי

<u>דו"ח מסכם: שילוב שיטות בקרה קרקעיות, צמחיות ואקלימיות לייעול ההשקיה</u>

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Final Report

Irrigation management using soil, meteorological and plant estimates of crop water use.

Yan Li, Y. Cohen, R. Wallach, S. Cohen, M. Fuchs, S. Moreshet

1. *Introduction of the experiment and treatment*

Water potential gradients drive water flow in the soil-plant-atmosphere continuum (SPAC). In this system, the water source is the soil, the atmosphere is the sink and plant functions as a capacitor and pathway. Irrigation prevents drying of the "source" to allow normal functioning of the plant and obtention of the expected yield. The management of irrigation deals with "when" to irrigate and "how much" to apply. Scientists and irrigation engineers have greatly improved the water use efficiency. In principle, irrigation control can be based on atmospheric demand, plant water status and soil water condition or the combination of them, whatever indicates that when the field needs irrigation and how much water to apply. The last two decades has seen the advent of computer control of automatic irrigation. However, it is our viewpoint that through a better understanding of water movement in SPAC we can achieve a simple procedure for farmer use (simple empirical model or easy-to-do measurement). For computer controlled operation, it is also important to need easy to get data only.

Based on the above considerations, the experiment was designed to measure parameters in the whole SPAC system: the meteorological parameters for determining the atmospheric demanding, the physiological characters of plant including water status and moving of water in the plant stem, growth rate (shoots and roots) etc.; root distribution, soil water conditions in the profile and the soil surface evaporation.

In order to get a better understanding of water flow processes in the SPAC system, the experiment was conducted with different treatments (3 treatment in 1995 and then it was modified to 2 treatment in 1996 and 1997). In the case of the experiment in 1996 and 1997, one treatment was designed to permit moderate stress from time to time by limiting or delaying the irrigation. Another treatment kept the soil water condition always favorable to the plant. Furthermore, in order to get wide range information under different soil conditions, the experiment was conducted in a clay-loam soil in 1996 and a sandy soil in 1997. The following rules controlled irrigation:

(1) Irrigation timing based on the ratio T/T_p, in which T was measured by the heat pulse system developed by Y. Cohen and T_p was calculated with a modified Penman-Monteith equation of M. Fuchs.

(2) The amount of water applied for each irrigation cycle depended on the total T_p of the whole cycle.

For treatment A (or so called dry treatment) a value of T/T_p below 0.6 of its peak value just after irrigation triggered the next irrigation. For treatment B (wet treatment), a T/T_p of 0.8 triggered irrigation. The amount of water applied on each irrigation cycle is 60% of total T_p for treatment A and 100% for B.

2 Set-up of the experiment

The experiment was carried out during the summer of 1995, 1996 and 1997. Based on our experiences of 1995 the design of the experiment was improved. Firstly, there were 2 treatments instead of 3 in 1995 to concentrate efforts on relevant matters.

The experimental field located at the campus of Volcani Center (ARO), Bet Dagan for 1995 and 1996 and the experiment farm of Faculty of Agriculture of Hebrew University, Rehovot for 1997. The plot with the two treatments is 1300 m^2 at Volcani and 1000 m^2 at the Faculty's experimental farm. The soil is clay-loam with significant spatial (vertical and horizontal) variance of texture at Volcani site and sandy at Faculty's farm with less significant spatial variance. Having considered the results from the first year's experiment, and the recommendation of the annual report reviewers we continued working on sweet-corn (*Maize L. vs. Jubilee*) in 1996 and 1997. By doing this, we think that we can approach the goals of the project more closely. The plant density is 8000 per 1000 m^2 with the row spacing of 0.95 m.

The irrigation system at Volcani site was a dripper system controlled by a hydraulic controller with the accuracy of 0.1 m^3. At Faculty site, the irrigation was controlled by computer with similar accuracy. The amount of water irrigated was recorded by a flow-meter with accuracy of 0.01 m^3 at the flow rate of >0.2 m^3/h. The dripper line with dripper every 0.5 m was put on each row of the crop on the row. Fertilizer was given through fertigation and the amount of fertilizer was applied according to the commercial practice. The management of the field, including weed and pest control followed commercial practice.

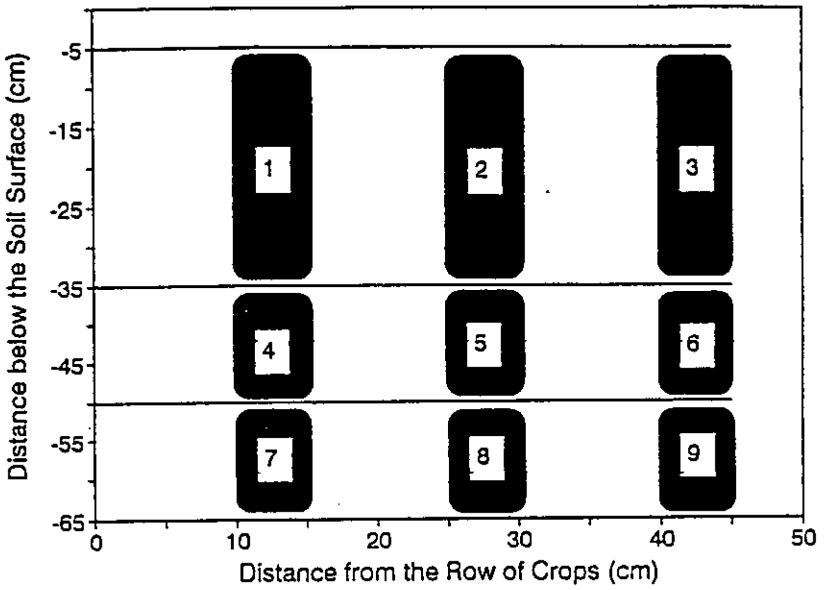
An automatic meteorological station was installed for the atmospheric parameters measurement. A data logger (CR-10, Campbell) attached to the station collecting the average of air temperature, humidity, wind speed, and solar radiation at a time step of 30 minutes. Transpiration was measured by the heat pulse system developed by Y. Cohen et al. in a selected representative sample of 10 plants for each treatment. The stomatal conductance of the leaves was measured with a porometer (LI-COR 1600) just after irrigation when the soil water condition was favorable to the plants and before irrigation when the plants were under water stress. Leaf conductance was also measured for the selected irrigation cycle everyday during noon hours in order to follow the changes during the cycle. Leaf water potential was measured in situ with a pressure chamber every noon during the experiment. In 1997, daily course of leaf conductance and leaf water potential were measured for 2 irrigation cycle in both treatment in order to study the cross relationship among canopy conductance, leaf water potential, transpiration and soil water condition. Infrared thermometers were installed above the canopy in the experiment of 1996 to monitor the leaf temperature and the data were recorded with the meteorological data simultaneously.

Root distribution was measured with a periscope at 40 (1996) and 56 (1997) tubes buried at different locations and different distance from the row. Different angles of installing the tubes (vertical in 1996 and 60° to vertical in 1997) were used based on our accumulation of the experience and the installation was carried with great care to ensure the tubes being in good conduct with the soil. Core sampling and trenching were employed as direct measurement of the root distribution and the results were intended to calibrate the periscope measurement.

Leaf area index was estimated directly by a destructive method (leaf area meter) from a running row length of 1 m and indirectly (Cohen et. al., 1997) with Decagon Sunlink throughout the growing season. The height and width of the plants were also measured every four or five days.

An automatic TDR system was installed for measuring the soil water content in the profile at a time interval of 0.5, 1 or 2 hours----depending on the scanning time for going through all the probes at two locations for each treatment. In 1996, at each location nine sensors were installed as shown in Fig.1:

Fig.1 Location of TDR Sensors,1996



Sensors No. 1-3 were 30 cm of length and the rest were 15 cm. All sensors were buried vertically with 2 rods 5 cm apart. Since the sensors were forced in, the soil was not disturbed. For the experiment of 1997, 16 sensors were installed at each location with 5 sensors on the layer of 5-20 cm, 20-35 cm and 35-65 cm below soil surface respectively and 1 sensor at depth of 65-95 cm. On each layer, 5 sensors were arranged as one on the row, 12.5 cm, 25 cm from the row on both side of the row. The single probe at the layer of 65-95 cm below soil surface was installed on the row.

Soil evaporation under the plant canopy was measured with the micro-lysimeters specially designed for this experiment consisting of PVC cylinders 15 cm in diameter and 15 cm in length. One end of cylinder was sharpened. The side wall were punched with holes to allow contact with the surrounding soil and root penetration. All the micro-lysimeters were buried at the beginning of the season then dug out, bottom and sides sealed by a polyethylene bag, and inserted at the site of evaporation measurement.

3 *Experimental results*

1) Irrigation, fertigation, growth and yield.

The irrigation, transpiration (measured by heat pulse), soil water loss (measured by TDR) for the whole season were summarized in Table.1 for 1996 and 1997. These three variables are in good agreement providing a very strong evidence for the successful measurements of heat pulse and TDR. The fertigation practice of 1996 is given in Table 2 (other fertilizers were applied before planting were not listed). Fertigation in 1997 (not listed) was carried out on each irrigation in accordance with local commercial practice on sandy soils.

Fig.2 Potential transpiration (Tp, empty circle), transpiration (T,filled circle) and the ratio T/Tp (filled square) during the experiment of 1996 and 1997. a---TMT A of 1996, b---TMT B of 1996; c---TMT A of 1997, d---TMT B of 1997.

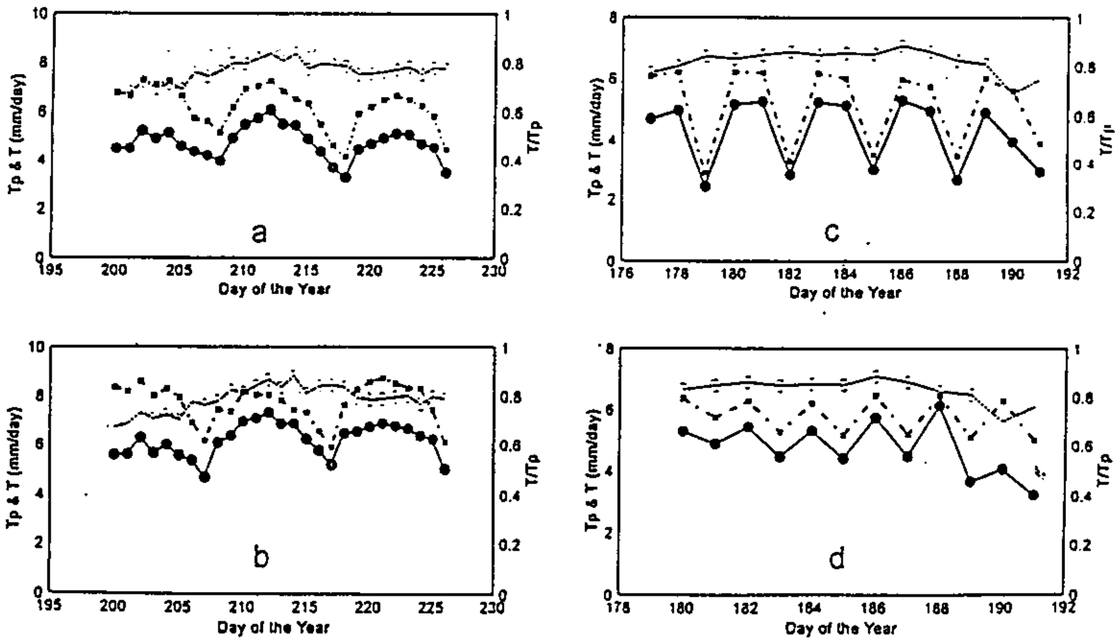


Table 1. Irrigation and water consumption

Plot 1 (dry TMT)			
Date	Irrigation (mm)	Tr (HP) (mm)	Water loss (TDR) (mm)
For the Year of 1996			
186	21.0		
191	25.2		
196-201	24.4		27.0
202-208	19.5	28.4	35.4
209-217	30.5	48.4	52.4
218-226	48.2	41.9	44.4
For the Year of 1996			
177-179	16	12.4	15.3
180-182	18	13.4	16.5
183-185	20	13.5	18.6
186-188	20	13.1	18.8
189-191	21	12.3	19.1
Plot 2 (wet TMT)			
For the Year of 1996			
183	9.1		
189	31.0		
197-201	32.6		35.7
202-207	24.5	25.9	32.4
208-217	43.7	59.6	54.2
218-226	83.8	48.3	52.4
For the Year of 1997			
180-181	14.4	10.3	13.5
182-183	14.4	10.1	13.3
184-185	16.0	9.9	14.7
186-187	16.0	10.2	14.4
188-189	16.0	9.6	14.9
190-191	16.0	7.4	14.5

Table 2. Fertigation of 1996 (unit: kg/1000 m^2 , fertilizer: Urea)

Date(Julian Day)	TMT 1 (dry)	Date(Julian Day)	TMT 2 (wet)
183	5	183	5
191	10	189	10
196	10	197	10
202	10	202	10

Growth of the plant shoots, it was expressed here in terms of LAI and plant height, was illustrated in S. Cohen's part of this report. With the results of S. Cohen's investigation, only plant height and width were measured during the experiment of 1997, which is sufficient to calculate LAI with known conclusions of his.

Harvest results of 1996 are summarized in Table 3:

Table 3. Final yield in both treatment (unit: kg/1000 m^2)

	Treatment 1(dry)		Treatment 2 (wet)	
	fresh weight	dry weight	fresh weight	dry weight
total shoots	5561.4	1179.0	6736.8	1401.3
fringe	1780.7	454.1	2052.6	507.0

The yield difference between the two treatments is small suggesting that plants in treatment 1 did not suffer severe stress during the whole season.

2) *Transpiration and soil moisture changes*

Transpiration and soil water changes are the main concerns of our study and of irrigation control in general. Heat pulse is a reliable method, at least for certain species which was calibrated, for measuring transpiration under field conditions when lysimeters are not available. Fig.2 gives the measured transpiration (T), calculated potential transpiration (T_p) and T/T_p on daily basis during the measured period (when the plants were young, heat pulse was not suitable to apply due to the fragile stem).

It is important to acknowledge that the fluctuation of T_p can be explained by the changing of LAI and the variation of the weather even though the summer weather of Israel does not vary much. The changing pattern of T actually combined 2 aspects of transpiration: the demanding represented by Tp and the supplying ability of the soil. The ratio, T/T_p, actually represented the sole meaning of soil water availability. The similarity of the changing pattern of T and T/Tp actually indicated the stable weather of Israeli summer.

It is interesting to notice that in Fig.2a & Fig.2b, T/Tp did not reach maximum immediately after irrigation. It reached the peak value usually at 2-3 days after irrigation. Further analysis would be needed to fully understand this phenomena. At least, however, 2 possible reasons could been accounted for: one is physiological, i.e., after going through certain stressed period the plant could not recover immediately after irrigation, another is the redistribution of soil water after irrigation, i.e., the overall soil water condition in the rooting profile might reach most favorable only 2-3 days after irrigation. This phenomena did not happen in 1997 on sandy soil (Fig.2c & Fig.2d) while the irrigation interval was much shorter.

TDR system did not work well automatically in 1996 as it did in 1997 due to technical reason of the TDR and the characteristics of the soil. As a result of manual measurement, the soil water content of 1996 gave only daily value even though 2-3 readings were taken everyday during the experiment. Fig.3 gives the layer average of soil water content for TMT A (dry) during the experimental course. It may be seen from Fig.3 most of the irrigated water went into the first 50 cm of the soil and most of the water loss occurred in the same layer. From the general increase of soil water content along the depth (even after irrigation) it can also be seen the difference of soil texture, i.e., the deeper the soil, the finer the texture the is. While in the sandy soil of Faculty's experimental farm, TDR worked very well automatically. It have reached such a high resolution that soil water changes can be distinguished on hourly basis. Fig.4 gives the soil water changes in one irrigation cycle for TMT A (dry) of 1997. The lines shown in Fig.4 was fitted line to filter the system noisy. It can be seen very clearly the soil water changes during day and night at different layer of the soil profile.

Fig.3 Soil water content from TDR
TMT A (dry), 1996

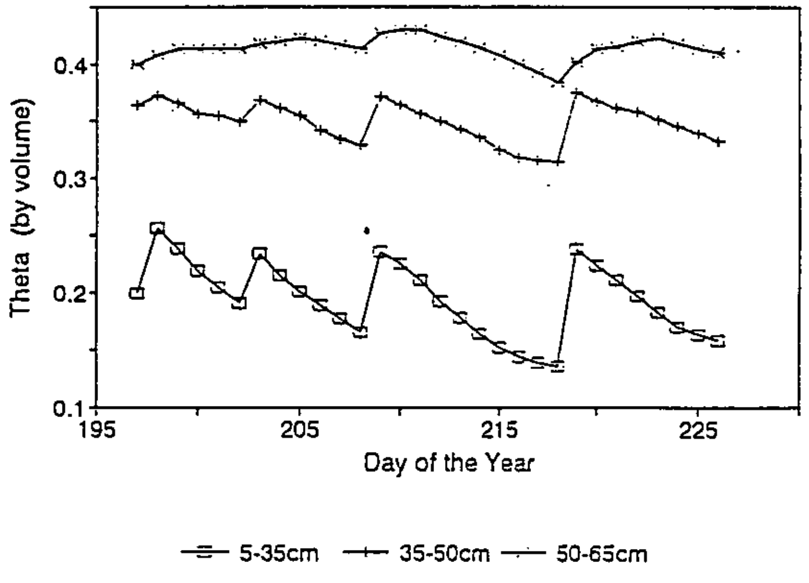
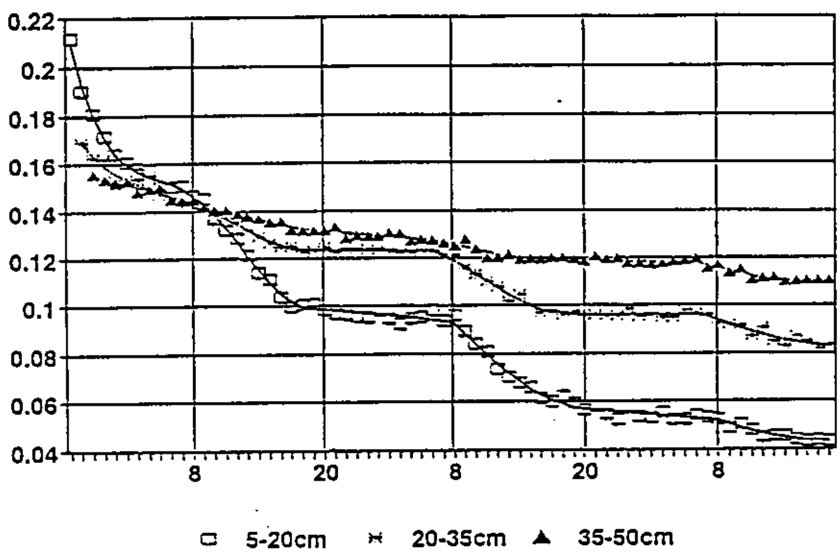


Fig.4 Soil water content from TDR

TMT A (dry), DOY 183-185, 1997



With the results shown in Fig.3 & Fig.4, soil water loss and soil water recharge after irrigation at different layers can be calculated. Fig.5 gives an example of soil daily water changes (positive number means water loss and negative means gain water) in one irrigation cycle at different layers for TMT A (dry) of 1996. The results are in good agreement with known fact that the root system extract water from deeper layer while the soil profile was drying. However, to get root water pattern for days just after irrigation will be a complex issue since soil water changes involved 2 significant processes during that time---water redistribution in the profile and root water uptake. For the year of 1997, soil water changes can be calculated on hourly basis as shown in Fig.4. Fig.6 & Fig.7 give 2 typical daily course of soil water loss from different layers of the soil profile. Fig.6 shows the day just after irrigation on TMT A (dry) while Fig.7 shows the day before irrigation when the plant was subject to water stress. It can be seen clearly that just after irrigation water loss mainly occurred at up layer of the soil profile while the root system had to take up big portion of water from deepest layer, the plant would soon be in stressed condition.

Since root water uptake was measured by heat pulse technique and soil water loss was measured by TDR, it is possible then to deduce leaching from the rooting soil profile if the soil water content in the whole rooting depth was monitored. As it can be seen in the following part of this report, at least for the experiment of 1997 the TDR sensors actually monitored the whole rooting depth of the soil profile.

Fig.5 Soil water changes in one cycle
TMT A-Dry, 1996

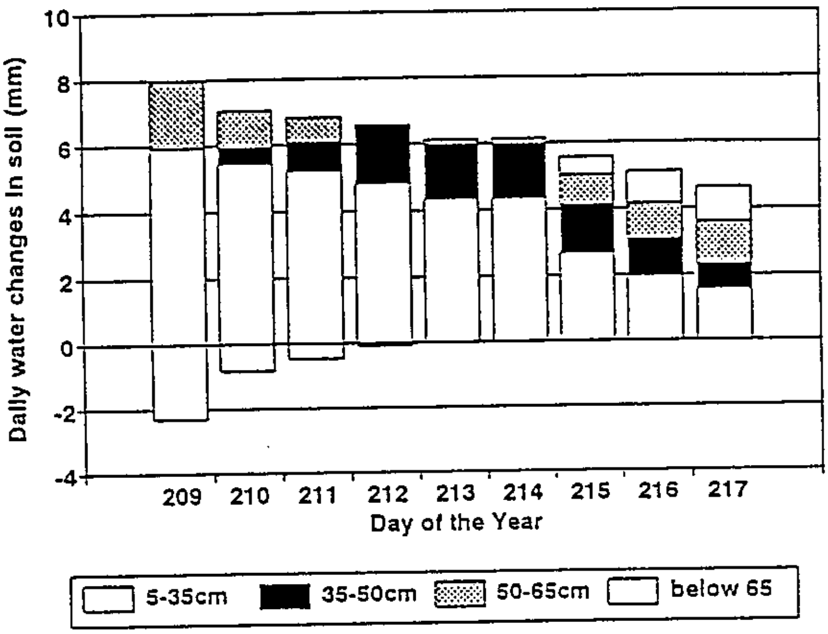


Fig.6 Water loss from different depth
DOY183,1996, first day after irrigation

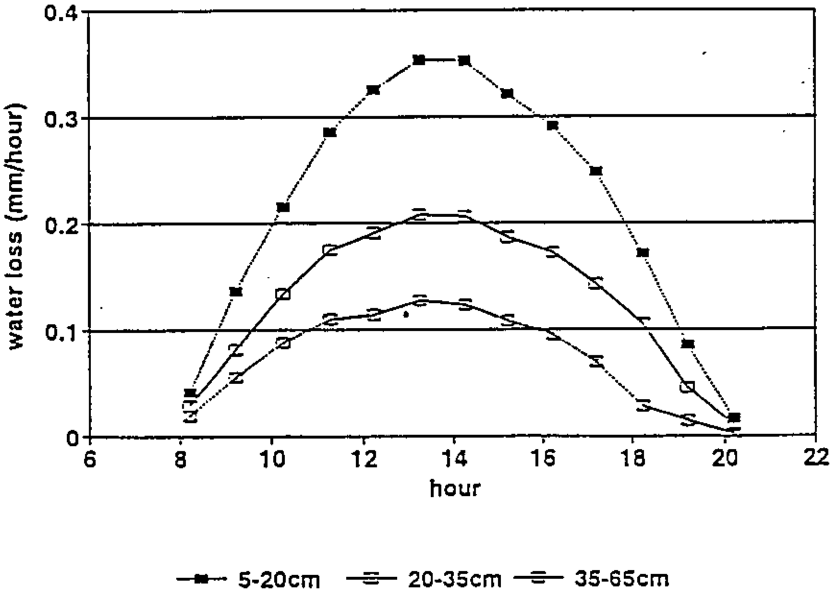
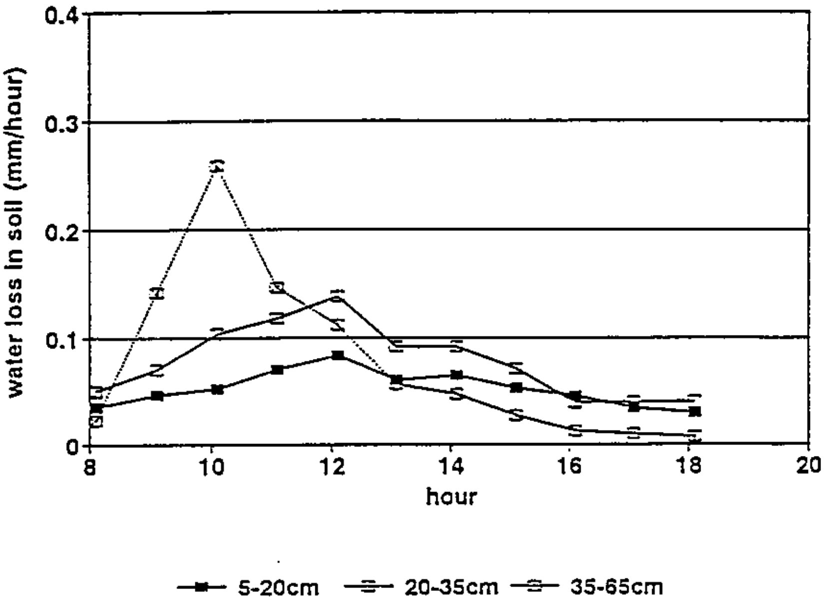


Fig.7 Water uptake from different layer
DOY182,1997, the day before irrigation



3) Root distribution

Great effort had been made to measure root distribution with periscope for it is a non--destructive method with the potential to monitor root distribution dynamically. However, the results from periscope are not satisfying even we did everything we could think of to minimize the preferential growth of root along the walls of periscope tubes. Comparing Fig.8 and Fig.9 it can be seen that the outcome of periscope measurement is systematically biased from the direct measurement. Generally, it underestimated the quantity of roots near the soil surface and overestimated it in the deep layers even though it detected the maximum quantity at the approximately the same depth (25-30cm below soil surface). Comparing periscope with another direct method, core sampling, instead of trenching shown in Fig.8, the results showed the tendency. That means that the results from periscope may not be considered as real root measurement before it is carefully corrected and calibrated.

4) Soil evaporation beneath canopy

Soil evaporation is only a minor component of SPAC water transport while the ground is fully covered by plant canopy. It may be main process of water consumption, however, at the beginning of growing season while the LAI is low. Therefore, soil evaporation is determined by 2 major factors: energy supply from the atmosphere after the interception of canopy and the wetness of soil surface. It is shown quite clearly in Fig.10 that how the LAI and the soil moisture at the soil surface (days after irrigation) affected the evaporation

Fig.8 root distribution (vertical)
average on the TDR sensing soil volume

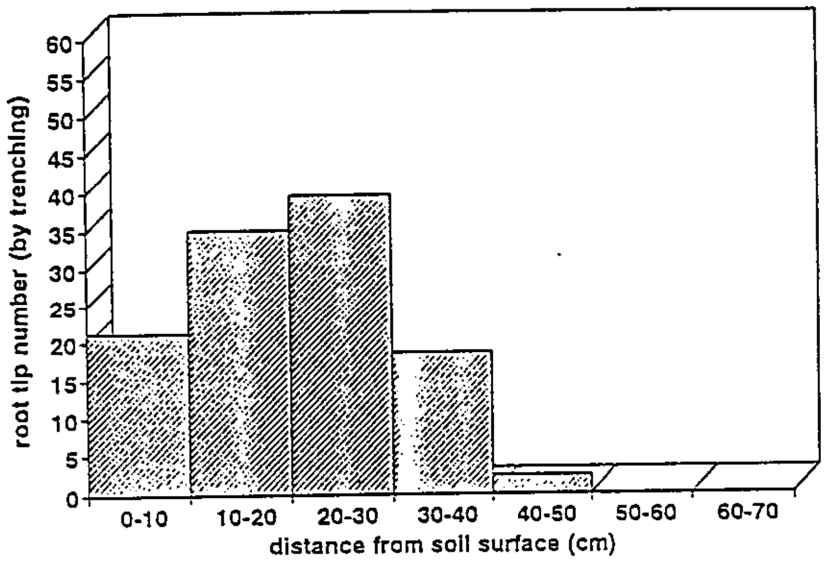


Fig.9 root distribution (vertical)
average on the TDR sensing soil volume

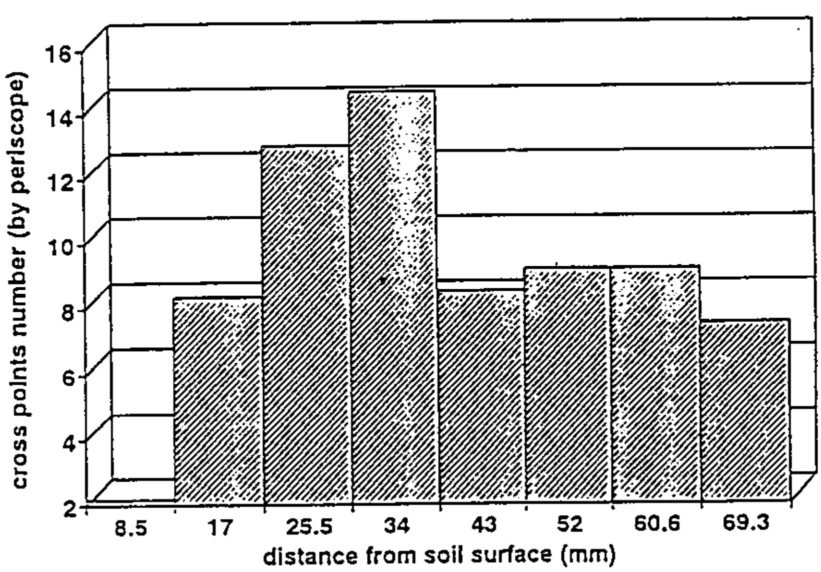
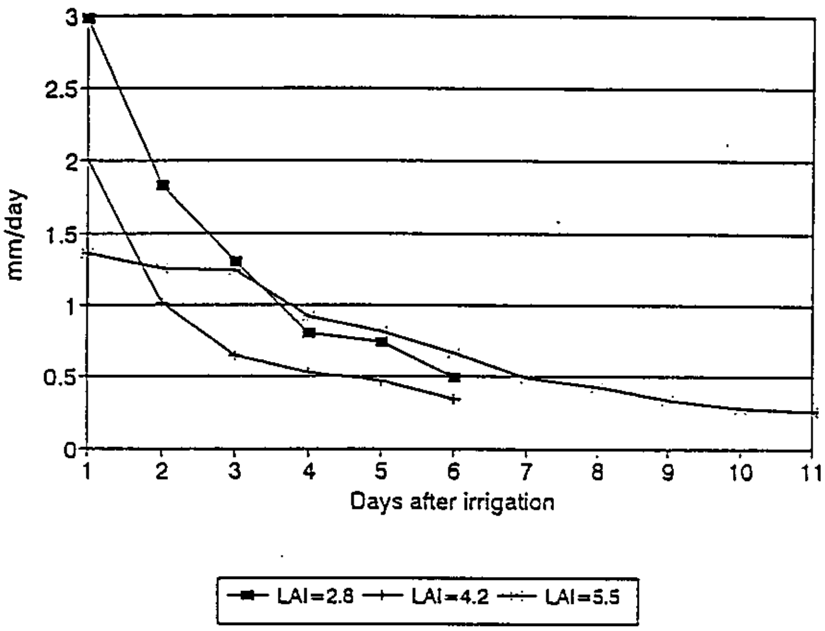


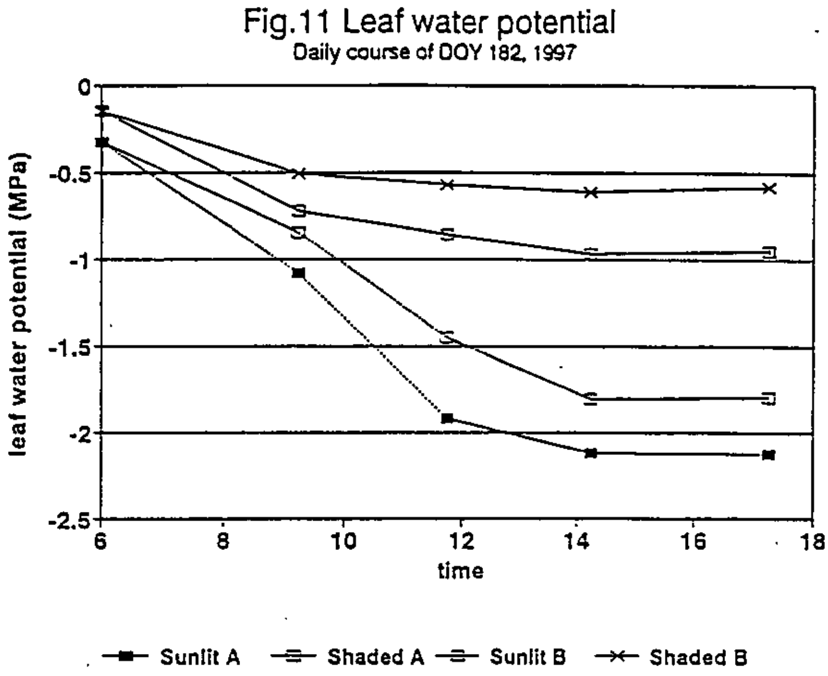
Fig.10 Soil evaporation beneath canopy
TMT B, 1995

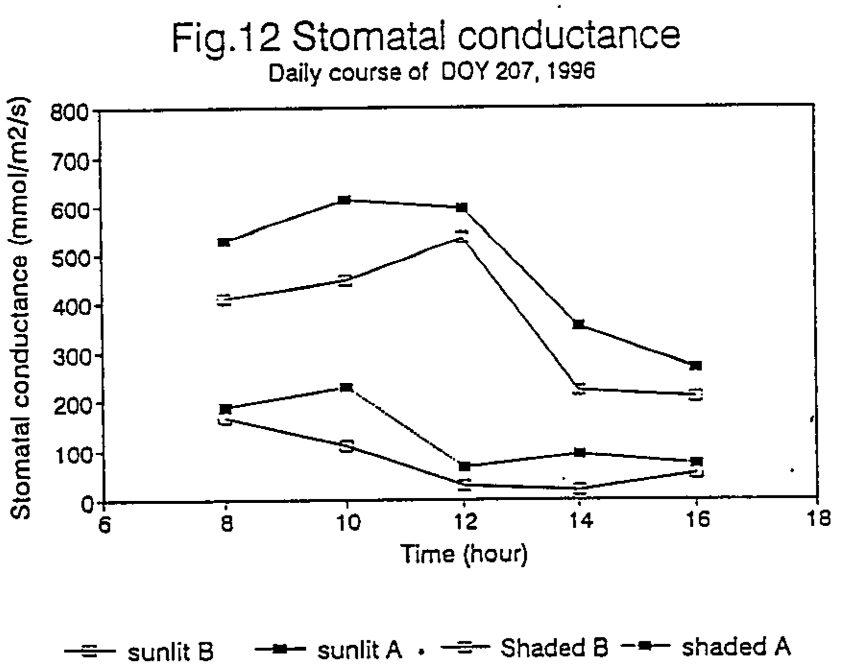


5) leaf water potential and stomatal conductance

Leaf water potential and stomatal conductance were considered indicators of plant water status. During the experiment, both parameter were measured simultaneously throughout the day on selected irrigation cycles (1997) or typical days (1996, 1995). Since leaves at different position of the plant canopy subjected to different radiation condition and therefore varied in water status, typical sunlit and shaded leaves were chosen for measuring leaf water potential so that it could be used to scale up to canopy level for further analysis. Example of the measurement were shown in Fig.11 for leaf water potential and Fig.12 for stomatal conductance.

Fig.11 shows that TMTA was on the day before irrigation while plants were subjected to water stress and TMT B was on the day before irrigation while the soil water condition is favorable. In Fig.12 it is shown that on the day before irrigation when plants in both treatment were subjected to certain water stress. It can been seen from Fig.12 that the daily course of stomatal conductance is more complex than leaf water potential under stressed conditions for soil and atmospheric condition might have different effects on them. Further study is still carrying on and results are expected in short time.





4 General estimation of the experiment and results to be expected

The whole experiment in general is highly successful especially in 1996 and 1997. Vast of amount of data on many aspects of water transport in SPAC were collected and deep analysis is still going on. Preliminary analysis shows that through this study we are able to contribute on many theoretical or practical approaches in this field.

Firstly, with combination of TDR and heat pules technique, plus direct measurement of soil evaporation, accurate results on root water uptake, leaching and soil evaporation beneath the canopy were obtained on daily even hourly basis. This enable us to study the transport process on its dynamic nature and give good estimation on water use efficiency under different irrigation regime.

Secondly, with the information on root distribution, soil water condition, root water uptake, leaf water potential and leaf conductance, a comprehensive investigation is carrying on to study the resistance for water transport on soil-root and canopy-atmosphere interface. The results are promising since it has rarely been seen in literature such a good set of data under filed condition. Breakthroughs are expected on the investigation of factors affecting canopy conductance and the relationship between root-soil and canopy-atmosphere resistance.

The third is technical aspects of studying SPAC water transport and the possible application on irrigation control. This can be seen partially in the following part of this report and our future publication.

Appendix I. Paper presented at The First Regional Conference on Interdisciplinary Strategies for Development of Desert Agriculture. Feb. 23-26, 1997. Sde Boker, Israel.

Canopy structure parameter estimation requirements for irrigation management

By Shabtai Cohen[1], Tatiana Milner, Yen Li, and Marcel Fuchs

Dept. of Environmental Physics and Irrigation, Institute of Soils and Water, A.R.O. Volcani Center for Agricultural Research, P.O.B. 6, Bet Dagan, Israel.

1 - email: vwshep@volcani.agri.gov.il

Keywords: Leaf area index, LAI, Penman, Transpiration, Model, Corn, Gap fraction inversion.

Abstract

Current knowledge of plant microclimate enables us to apply evaporation models like the Penman equation to whole plants and crops in order to determine actual transpiration without the need for empirical coefficients. We propose to use this approach in order to determine crop water requirements for irrigation management. This study examined the sensitivity of crop transpiration to LAI and other canopy structure parameters using a transpiration model and measurements of canopy structure and transpiration in a corn crop at Bet Dagan, Israel.

The model was validated by comparison with three sets of sap flow measurements in the corn crop. Predicted transpiration was not significantly different from measured transpiration at $p > 0.95$.

The important plant parameter for estimating transpiration is LAI. However, the sensitivity of transpiration is inversely related to LAI. For 10% accuracy in transpiration estimation, LAI should be determined with better than 20% accuracy for values below 3, while for LAI > 3 20% accuracy is acceptable.

Sensitivity of the model to characteristic leaf dimension and wind speed height were minor for a large range of values. For crops that attain full cover during development (e.g. corn) sensitivity of transpiration to crop geometry (i.e. row width and direction) is minor and can be ignored.

Leaf angle distribution was found to have a significant effect on transpiration especially for high values of LAI.

Determination of LAI with gap fraction inversion, and by correlation with growing degree days and plant height were evaluated. The plant height correlation was found to be most appropriate for use with the model because it is best for small plants. For crops where this correlation has not been determined or is not applicable (e.g. tree crops) the gap fraction inversion technique will be useful. This study demonstrates the need for development of protocols for accurate LAI determination with gap fraction inversion.

Introduction:

Crop water requirements are generally determined from climatic evaporative demand by using a crop coefficient describing the relationship of crop transpiration to evaporative demand (Doorenbos and Pruitt, 1975; Hill, 1991). Even though recent applications of this technique utilize polynomial equations to describe the change in crop coefficient during crop development (Hill, 1991), the polynomial parameters are by definition empirical.

Current knowledge of plant microclimate enables us to apply evaporation models like the Penman equation to whole plants and crops in order to determine actual transpiration without the need for empirical coefficients (e.g. Petersen et. al., 1992). We propose to use this approach in order to determine crop water requirements for irrigation management. But this application depends on the ability of the farmer to obtain the following input data in real time:

- climate data from a standard weather station
- canopy structure information - especially leaf area index (LAI)

Recent advances in data communications make online access to climate data from weather stations feasible, and computers that can perform the necessary calculations are readily available. A pilot program with a weather station network to provide data for evaporation calculations is currently running in Northern Israel (M. Meron, MIGAL, Kiryat Shemonah, Israel).

Collection of canopy structure information is still problematic, and until recently there were no practical ways to measure LAI. Advances in application of the gap fraction inversion technique with commercial instrumentation (Welles and Cohen, 1996) may provide the tool that will give this approach widespread general applicability. However, the gap fraction method is not perfect, and therefore it is timely to evaluate the accuracy requirements for canopy structure measurement for use in calculating transpiration.

We examined the sensitivity of crop transpiration to LAI and other canopy structure parameters using a transpiration model and measurements of canopy structure and transpiration in a corn crop at Bet Dagan, Israel. The sensitivity was then used to evaluate accuracy requirements for the determination of LAI and other parameters, in order to obtain a fixed accuracy in irrigation quantities. Requirements were then compared with the performance of several methods for determining LAI.

Theory:

The transpiration model:

Leaf transpiration (E) was computed using the Penman-Monteith combination equation for amphistomatous leaves (Monteith, 1965 and 1973):

$$\lambda E = [s R_n + \rho c_p (e_s(T_a) - e_a)/r_u]/(s + \gamma + \gamma r_s/r_u) \qquad (1)$$

$$r_u = r_a + r_b/L$$

where s is the slope of the saturation vapor pressure curve (kPa °C^{-1}), γ is the psychrometric constant (kPa °C^{-1}), R_n is the net radiation flux density (MJ m^{-2} s^{-1}), ρ is the density of air (kg m^{-3}), c_p is the specific heat of air (MJ m^{-2} s^{-1}), $e_s(T_a)$-e_a is the air water vapor pressure deficit (KPa), r_s is stomatal conductance, r_b is leaf boundary layer conductance, r_a is the aerodynamic resistance (s m^{-1}), and L is the leaf area index under consideration.

Net radiation, R_n was computed as:

$$R_n = L [\alpha (f K_r + X K_f) + X R_l] \qquad (2)$$

where α is the leaf absorption coefficient for short wave irradiance, taken as 0.5 (Jones, 1992), K_r and K_f are the direct and diffuse flux densities of short wave irradiance, respectively, R_l is the exchange of long wave radiation between exposed leaves and sky, f is the ratio of leaf area projection in the plane perpendicular to the sun's rays and the actual leaf area (sometimes called the extinction coefficient), and X is the view factor for isotropic radiant transfer between leaves and sky. Long wave interchange between leaves was neglected, as radiant transfer between leaves in the temperature range encountered is negligible.

The extinction coefficient, f, was computed for an ellipsoidal angular distribution of leaf area (Campbell, 1986) as:

$$f(\theta) = (Y^2 + \tan^2 \theta)^{0.5}/D \qquad (3)$$

where Y is the ratio of vertical to horizontal leaf projections, θ is the solar zenith angle, and

$$D = 1.47 + 0.45\,Y + 0.1223\,Y^2 - 0.013Y^3 + 0.000509Y^4$$

The view factor for diffuse exchange between leaf and sky, X, (after Fuchs et. al., 1987) is defined as

$$X = (1/\pi) \int_0^{2\pi} \int_0^{\pi/2} \exp(-f(\theta)\,L) \sin\theta \cos\theta \, d\theta \, d\phi \qquad (4)$$

where ϕ is the azimuth angle. The integral (4) was computed numerically for half canopy LAI, and this value was used as a constant for sunlit and shaded leaves.

Short wave irradiance components and an index of sky clearness, C, were computed as follows. Initial values, K_r' and K_f', were computed from the algorithm suggested by Campbell (1977) for clear skies based on extraterrestrial radiation and average atmospheric transmissivity. These values were adjusted according to actual measured global irradiance, K_t, as follows:

$$\begin{array}{ll} K_r = K_t - K_f' ;\; K_f = K_f' ;\; C = 1. , & K_r' + K_f' < K_t \\ K_r = K_t - K_f' ;\; K_f = K_f' ;\; C = K_t/(K_r' + K_f') , & K_f' < K_t < K_r' + K_f' \\ K_r = 0 ;\; K_f = K_t ;\; C = K_t/(K_r' + K_f'), & K_t < K_f' \end{array} \qquad (5)$$

Long wave interchange with the sky, R_l, was computed as

$$R_l = C\,(\varepsilon_s - 1)\,\sigma\,T_a^4 \qquad (6)$$

where σ is the Stephen-Bolzman constant, T_a is air temperature, and ε_s is sky emissivity, taken after Brutsaert (1982) to be

$$\varepsilon_s = 0.52 + 6.64 * 10^{-3} * e_a^{0.5} \qquad (7)$$

and e_a is air humidity in Pa.

Aerodynamic and boundary layer resistances were calculated after Cohen et. al. (1995) using wind speed measured at height z, measured crop height, and a mean leaf dimension taken as the average width of mature leaves. Equation (1) was solved separately for sunlit and shaded leaves, taking into consideration the leaf area index of each group. Sunlit leaf area index, L_s was computed as:

$$L_s = (1 - \exp(-f\, L_t))/f \qquad (8)$$

where L_t is total leaf area index.

Correcting transpiration for row dimensions:

Row dimensions cause additional shading of plant parts. This was accounted for by assuming a rectangular row shape with height h and width w. Leaf area index, L_t, was then corrected for the calculation of sunlit leaf area index (in eq 8) according to the total fraction of the ground in shadow, as follows:

$$L_t' = d * L_t /(w+s) \qquad (9)$$

where s is the length of shadow cast by the row perpendicular to the row.

As the energy balance expresses the flux densities based on the total ground area, the effective sunlit exchange area (L in eq 1) later becomes:

$$L_s = (w+s) * L_s / d \qquad (10)$$

Plant shadow length perpendicular to the rows (s), derived from simple geometry, is computed from canopy height (h), solar zenith angle (θ) and azimuth angle (ϕ_s), and row direction (ϕ_r) as:

$$s = h * (\tan\theta \sin(\phi_s - \phi_r)) \qquad (11)$$

Leaf resistance:

Leaf resistance was assumed to be influenced only by incident photosynthetic irradiance, in an hyperbolic relationship. It was computed after Saugier and Katerji (1992) as:

$$r_l = r_{l\,min} (1 + M/Q) \qquad (12)$$

where $r_{l\,min}$ is the minimum stomatal resistance for the plant species, and M is the irradiance for obtaining twice $r_{l\,min}$. Typical fitted values for well irrigated corn, based on Shawcroft et. al. (1974), are 97 s m^{-1} and 277 μmol m^{-2} s^{-1}, respectively.

Materials and Methods

The measurements were made in well-irrigated corn fields (Zea mays, variety Jubilee Sweet) in Bet Dagan (32°00'N 34°49'E, 50 m above mean sea level) during the summers of 1994, 1995 and 1996. Rows were seeded 95 cm apart and mean plant density along the row was 9.5 plants/m with a standard deviation of 1.6 plants/m. Row azimuth was 17° (clockwise from N).

Destructive sampling for leaf area was done by harvesting a 1-m run of plants, and measuring their leaf area with a Delta-T video camera and image-analysis type leaf area meter (accurate to ±3%). Lengths and mean diameters of stems and fruits were used to compute half of their surface area, and this was added to the leaf area. For each of the two samples taken when LAI exceeded 6, one typical plant was measured and its area was extrapolated on the basis of the number of plants per meter of row counted near that plant.

Canopy height was measured at least once a week and values for intermediate days were interpolated. To determine the canopy height, maximum leaf heights in each of 20 one-meter-long sections of the row were averaged.

Inversion measurements of LAI and the ratio of vertical to horizontal leaf projections (Y in equation 3) were made with line photosensor arrays (LPA) probes (types Sunlink and Ceptometer, Decagon Devices, Pullman, WA), using the method described by Cohen et. al. (1997).

Grids for monitoring canopy development with the LPA probes were set by placing 1-m-long rulers below the canopy, extending from one row stem line to the next. Rulers were placed in pairs so that the LPA probe could be positioned parallel to the row at different distances from it. Pairs of rulers were placed in 15 even-looking parts of the field. The rulers remained in these measurement positions for the full course of crop development. Measurements were made every 10 cm along the rulers, starting 5 cm from the stems.

Air temperature, relative humidity, wind speed, and global radiation were measured with an automatic weather station (Campbell Scientific Inc., Logan UT), mounted on a 4 m high tower.

Growing degree day index (GDD) for corn was calculated after Dwyer and Stewart (1986) as:

$$GDD = \sum_{t_1}^{t_2} [(T_{max} + T_{min})/2 - 10] \qquad (13)$$

where $[(T_{max} + T_{min})/2 - 10] \geq 0$. T_{max} and T_{min} are daily maximum and minimum air temperature and t_1 and t_2 are day numbers of two sequential stages in crop development.

Solar angles were computed after Paltridge and Platt (1976).

Transpiration of corn plants was measured with the heat pulse method described by Cohen (1994) and validated for corn by Cohen and Li (1996). Unfortunately, this method cannot be used for small plants. Therefore the measurements started only when LAI exceeded 4.

<u>*Results and discussion:*</u>

a. model validation:

Figure 1 shows the development of LAI as measured in the two irrigation treatments in July, 1996. The fast development of corn in our hot summer results in the crop's going from seedlings to LAI>5 in less than 20 days; or an increase of one LAI every 4 days. The influence of the fast growth on LAI estimation requirements is discussed below.

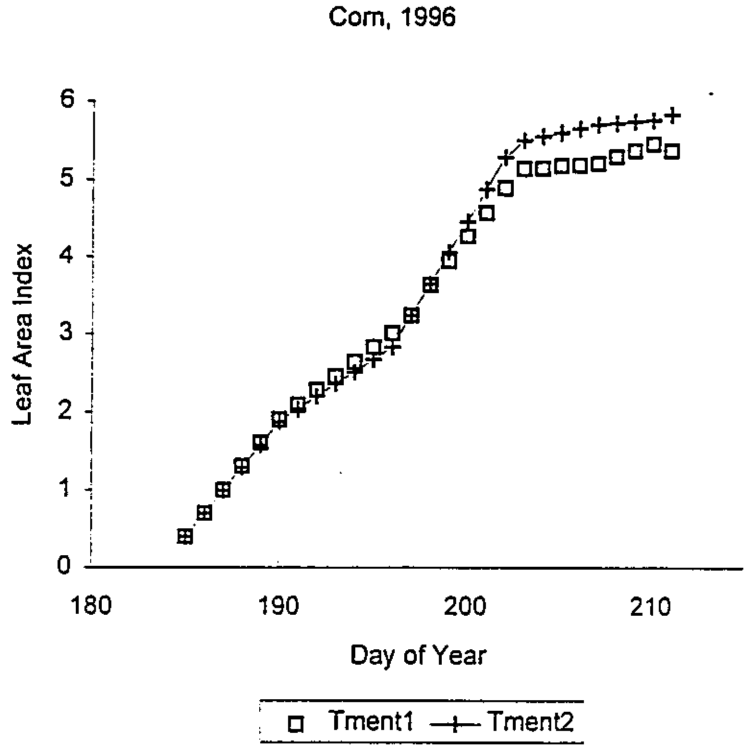


Figure 1. Corn leaf area index development in two non-limiting irrigation treatments during July of 1996.

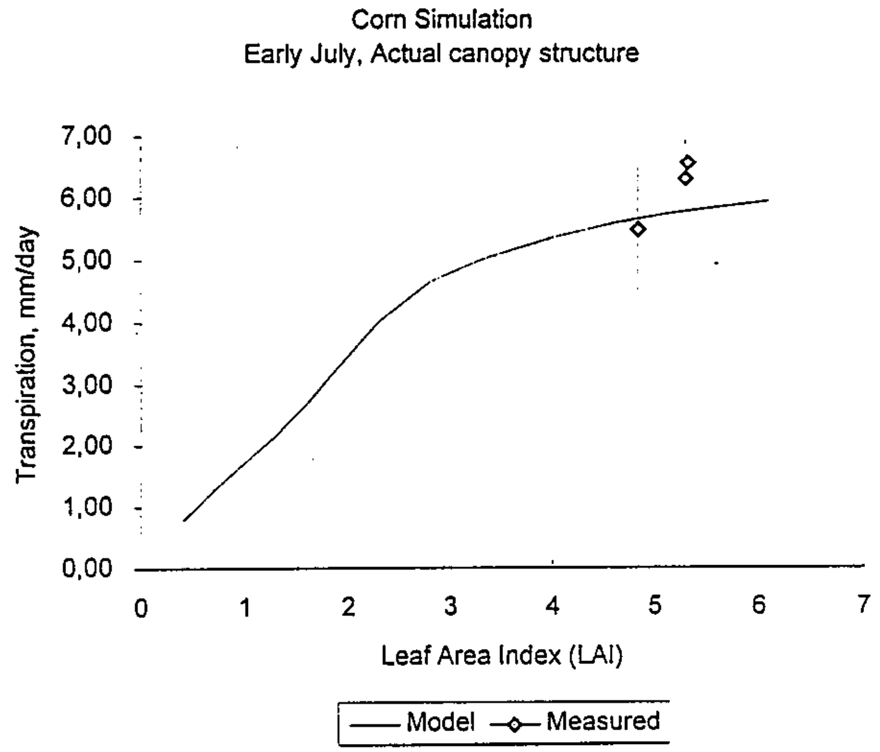


Figure 2. Simulated and measured corn crop transpiration as a function of leaf area index. The simulation was done with actual measured canopy structure during development (i.e. LAI and row width and height) and average climate conditions for the beginning of July.

Figure 2 shows predicted transpiration from the model, along with three groups of validation measurements. Environmental conditions used for the model simulation were averages for early July, based on data collected with the automatic weather station. Plant parameters (i.e. LAI and crop width and height) were those measured during crop development. Each group of transpiration measurements represents 10 plants measured for approximately 5 days during the wet portions of an irrigation cycle, before a noticeable decrease in transpiration due to soil moisture depletion occurred. The vertical bars are 95% confidence intervals for the mean transpiration. It is clear that the model predictions are close to the measured values, and well within the confidence interval for the means. We assume that the fit would be improved if the model were to use actual environmental conditions for each day of measurement, instead of the average climate values used here. This (fig. 2) is taken as a verification of the model, since measurements of smaller plants were not possible with the heat pulse technique.

b. temporal changes in transpiration and LAI:

Figure 3 shows the derivative of transpiration with respect to time as a function of increasing leaf area index. This can also be seen as the error in predicted transpiration due to an error of one day in LAI determination. The figure shows that when LAI is less than 2 the derivative is high because of the rapid increases in transpiration during this initial stage of crop development. Later the derivative is small, indicating that precise timing of LAI determination is less important. If our goal were to estimate transpiration to within 0.5 mm day^{-1}, then when leaf area were less than 2, daily estimates of LAI (from measurement or interpolation) would be used in the model. When LAI exceeds 4, LAI development slows and timing of LAI estimation is less critical.

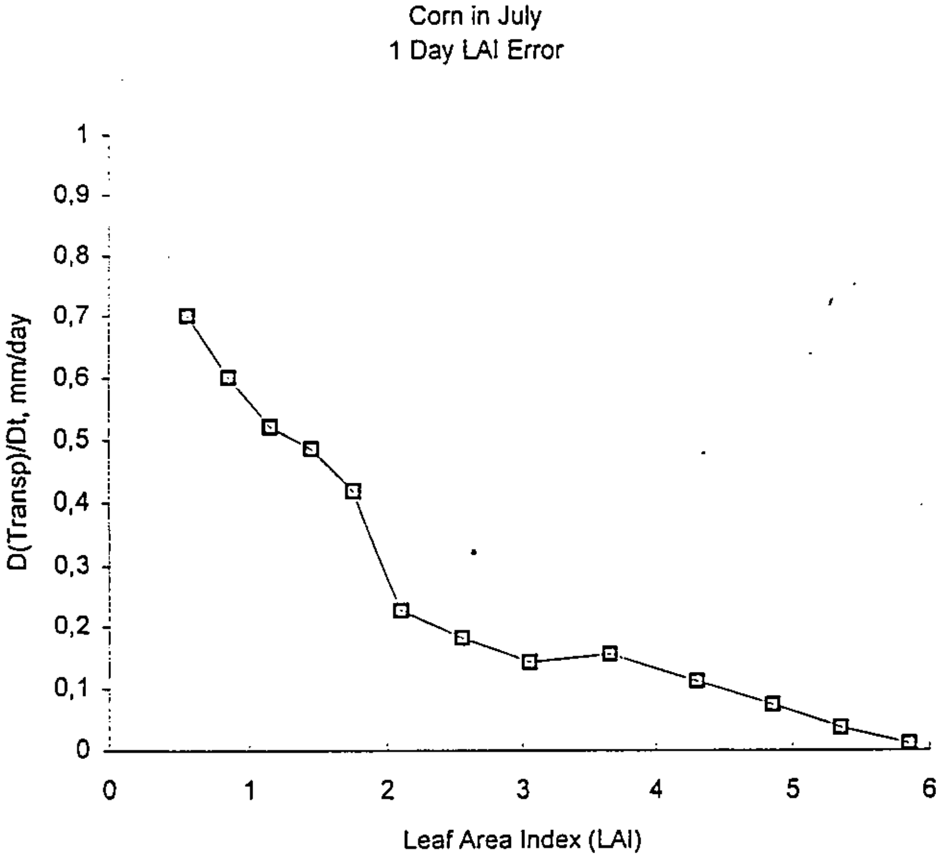


Figure 3. The time derivative of transpiration as a function of leaf area index for the

corn crop in July, 1996. The derivative can also be viewed as a one day error in LAI input into the model.

c. sensitivity to crop parameters:

Crop parameters in the model can be divided into two groups: plant characteristics, and row geometry. Plant characteristics include:

- LAI
- characteristic leaf dimension
- leaf angle distribution parameter (in our case the ratio of vertical to horizontal projections)

Row geometry parameters are:

- Crop height
- Row spacing
- Row width
- Row azimuth angle
- Wind speed height

The model was tested for sensitivity to each of these parameters using the information collected in the corn crop.

d. Sensitivity of transpiration to plant parameters:

LAI:

Figure 4 shows the influence on transpiration of a 20% error in LAI determination, as a function of LAI. This figure was computed because 'good' non-destructive LAI determination techniques are accurate to within 20% (Welles and Cohen, 1996). The figure shows that the largest error in transpiration, approximately 0.5 mm/day, occurs when LAI is between 1 and 2. Later in development the error decreases, even though crop transpiration still increases rapidly with increasing LAI until approximately LAI 4 (see fig 2). Figure 5 shows the relative error in crop transpiration. The figure shows, for example, that if we require 10% accuracy in determining transpiration, then LAI estimation with 20% accuracy is only acceptable when LAI exceeds approximately 3.

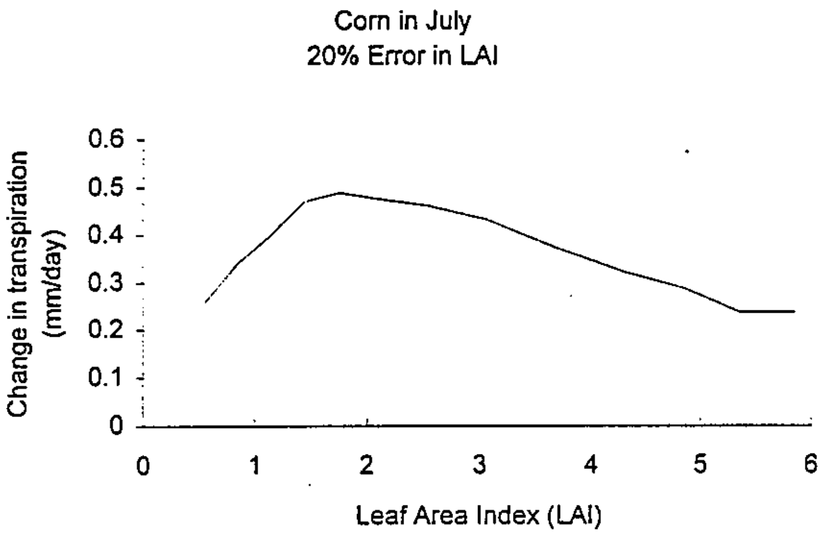


Figure 4. The sensitivity of simulated transpiration to a 20% error in the determination of LAI.

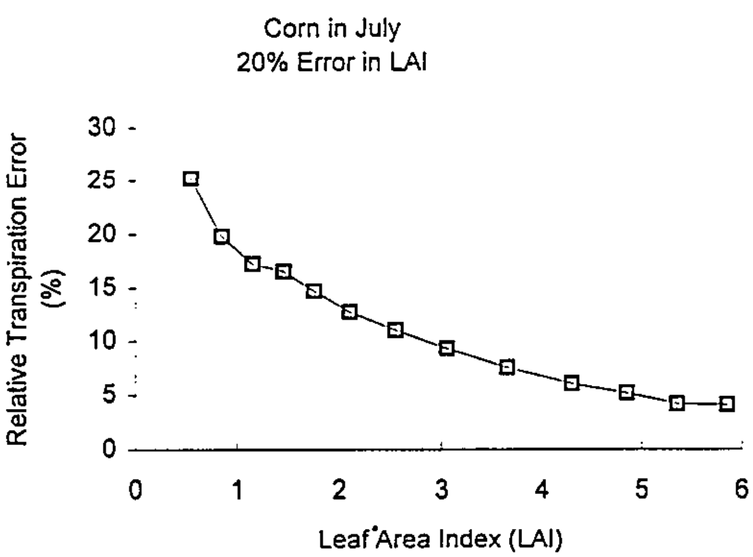


Figure 5. The relative sensitivity of simulated transpiration to a 20% error in the determination of LAI.

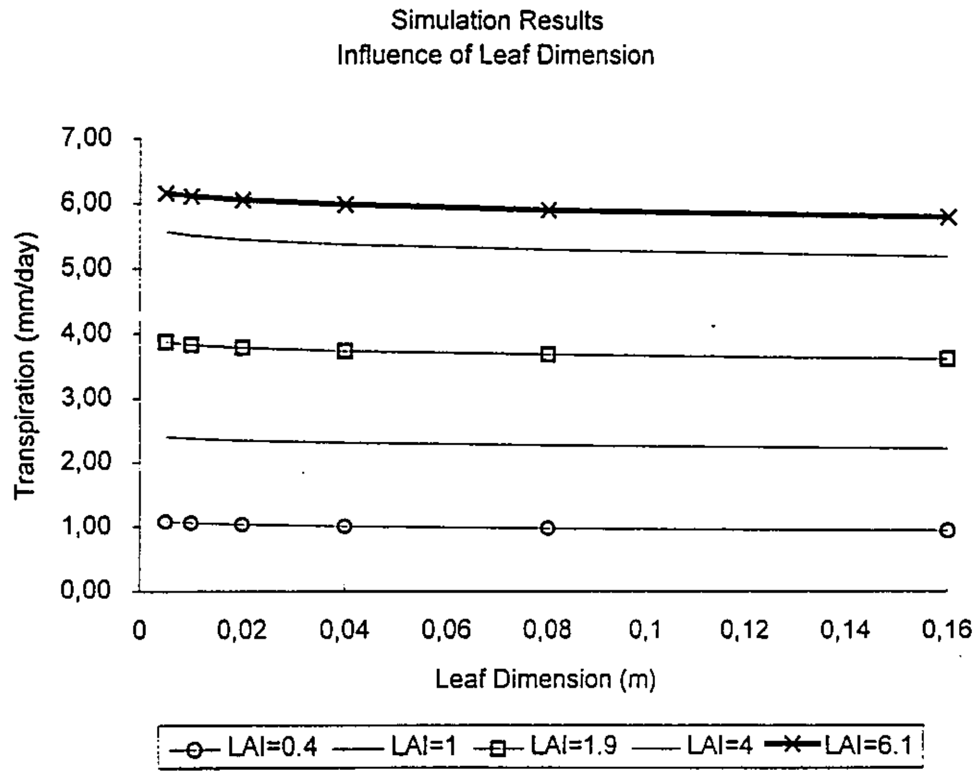


Figure 6. The influence of characteristic leaf dimension (see Theory) on transpiration for a number of LAI values, calculated using measured crop parameters.

Characteristic leaf dimension:

Figure 6 shows transpiration as a function of characteristic leaf dimension for a number of LAI values. It is clear that the model is not very sensitive to this parameter at any of the LAI values. For LAI values exceeding 1, a change of an order of magnitude in leaf dimension (i.e. from 0.01 to 0.1 m) changed transpiration by approximately 5%. We can therefore conclude that relative to the inaccuracy of LAI estimation, inaccuracy in transpiration estimation due to errors in leaf dimension are small. A table of characteristic values for each crop should be adequate.

Leaf angle distribution:

Figure 7 shows transpiration as a function of the ellipsoidal leaf angle distribution parameter Y (from eq 3). Campbell (1986) showed that in erectophile canopies, like soybean, Y can be as low as 0.8, while for planophiles, like sunflower, Y exceeds 4. For our corn crop, Y varied from 0.5 for young plants to 1.6 at maturity. Fig

7 shows that transpiration is most sensitive to Y for erectophile canopies, when Y<2. The largest influence on transpiration is when LAI is large, when vertical leaves increase the amount of midday sunlit leaf area and increase transpiration. This is seen more clearly in figure 8, which shows transpiration as a function of LAI for 3 values of Y and for the corn crop. Analysis of the relative difference in transpiration between an erectophile canopy (Y=0.25) and a panophile (Y=4), in figure 8, shows that in the range of LAI from 0.5 to 6 there is a positive linear relationship between the relative difference in transpiration and LAI. For low values of LAI transpiration of erectophiles can be more than 20% less, while for LAI=6 transpiration of the erectophile is 20% greater. Since at low LAI transpiration is small, and commonly soil evaporation is relatively large, the difference at low LAI is less important than that at high LAI. We therefore conclude that leaf angle distribution should not be ignored, especially for large canopies.

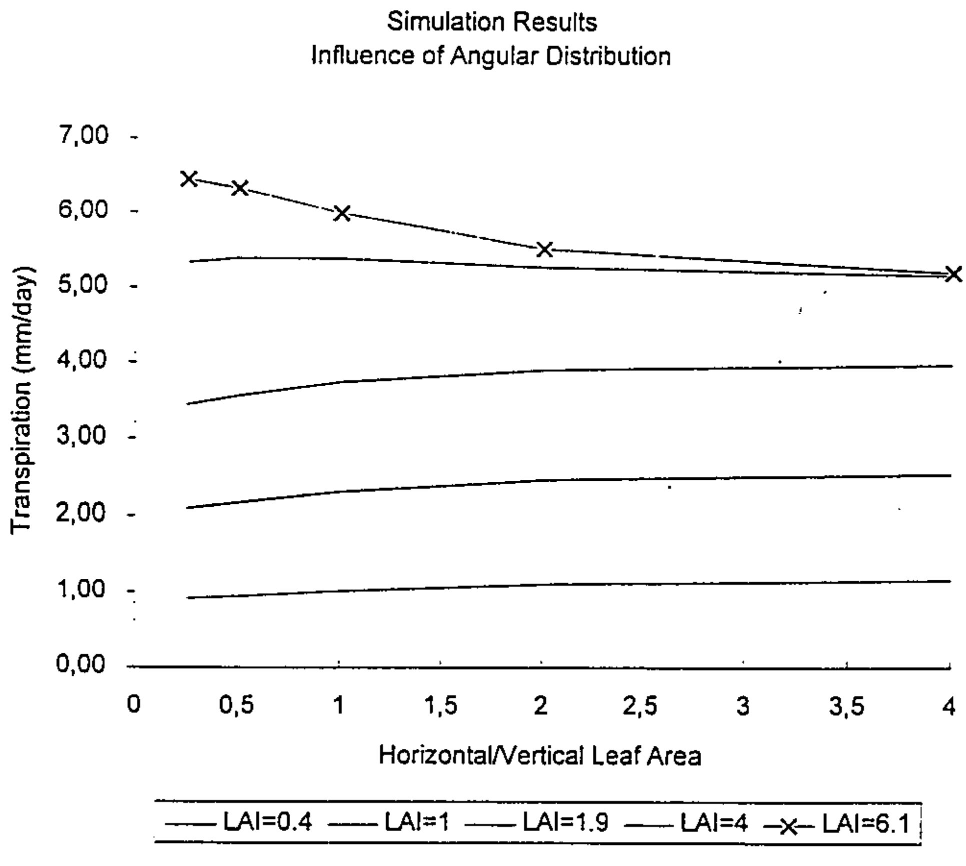


Figure 7. The influence of leaf angle distribution on transpiration for a number of values of LAI.

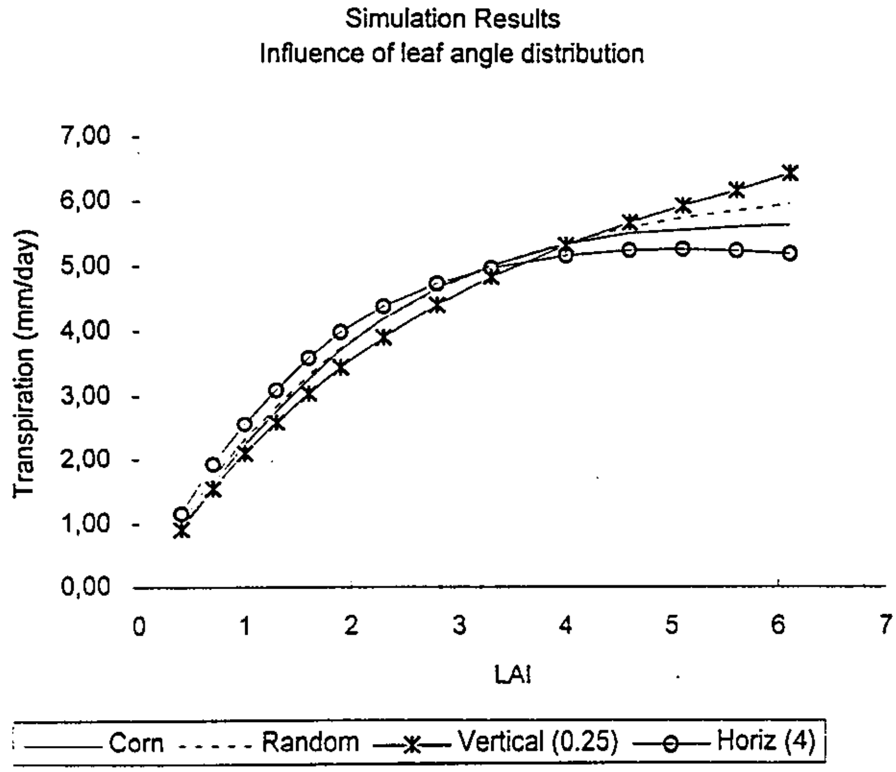


Figure 8. Transpiration as a function of LAI for three leaf angle distributions.

e. Sensitivity of transpiration to row geometry parameters:

Row geometry parameters, i.e. row width, height, spacing and direction, influence the relative amounts of sunlit and shaded foliage (see equation 10). In general, the more space there is between the rows, the smaller the ratio of sunlit to shaded leaf area, and therefore, for normal summer conditions, the less the transpiration. In the case of our corn crop the inter-row space was filled with foliage before LAI 3, and simulation of changes in row direction and small changes in crop width showed insignificant differences from full row cover. The influences of changes in row direction and increasing planting distance can be seen in figure 9, which shows simulated results for 3 m planting distance using measured crop width and height. The simulated (and validated) curve for our corn crop is included for comparison. It is clear that changes in row structure can cause significant changes in (simulated) crop transpiration. However, it should be noted that the canopy simulated in figure 9 is somewhat unrealistic because if our corn rows (with 9.5 plants per meter of row) were planted at a 3m row spacing, LAI at full development would not exceed 2.

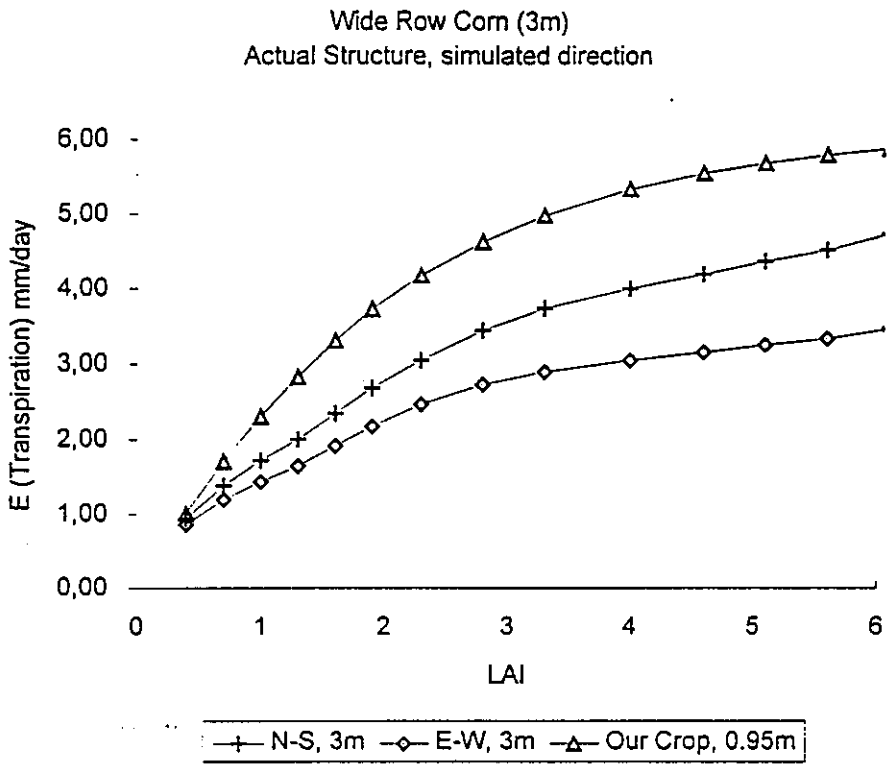


Figure 9. Transpiration as a function of LAI for two row directions planted at 3 m spacing using canopy structure measured in the corn crop (0.95 m spacing).

In view of the results discussed above it may be wise in situations where rows close early in crop development to omit the row geometry corrections in the simulation, since errors in user inputs of these parameters can cause significant errors, while the influence of row geometry on transpiration is small.

Wind speed height

The height of windspeed, usually measured at a standard meteorological station, is also an input in the model. The model is not very sensitive to this value, as seen in figure 10, as long as the windspeed is measured above the crop. It would therefore be wise when implementing the model to select a standard height above the crop as the input value for this parameter.

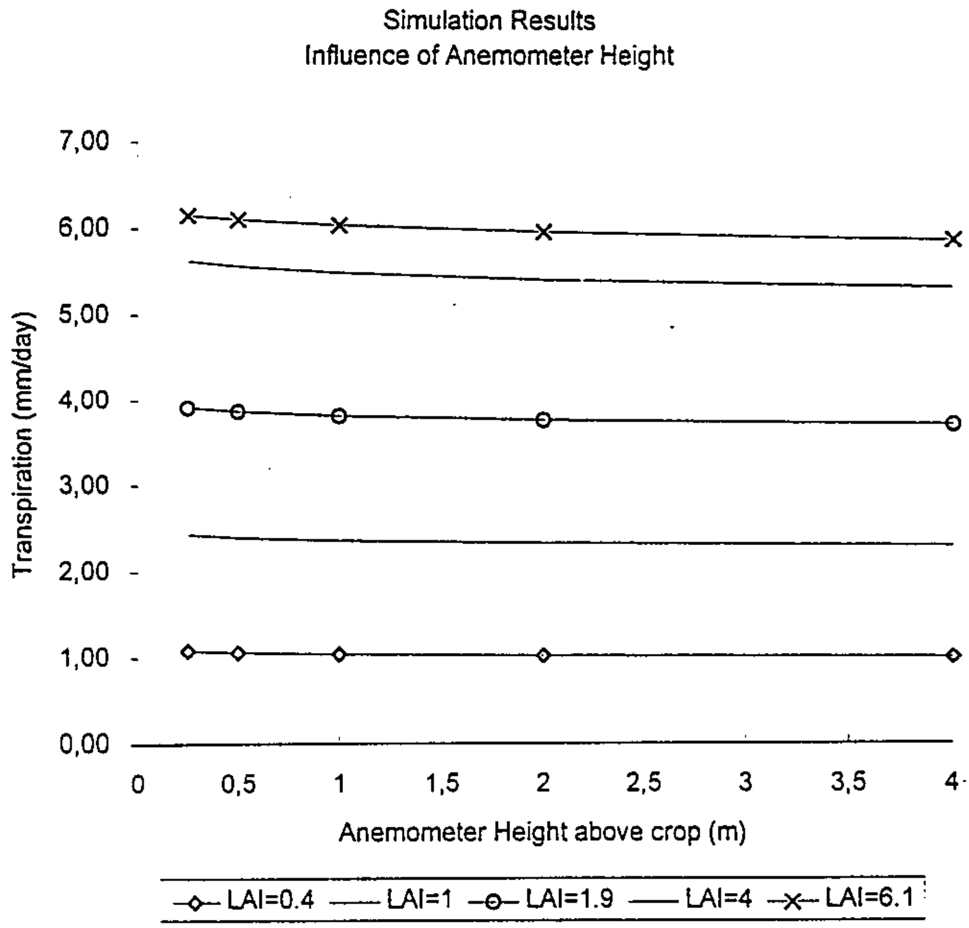


Figure 10. Transpiration as a function of wind speed height above the crop for several LAI values.

f. Alternatives for LAI estimation:

It is clear from the results that LAI is the most important parameter for accurate transpiration estimation. We now turn to different possibilities for simple estimation or measurement of LAI. Figure 11 shows the relationship of LAI to Growing degree day index (GDD) computed from day of emergence. Although a direct relationship is evident, especially for the first part of LAI development, there were large differences between the two growth periods (July and September). These differences introduce an uncertainty of greater that one LAI at LAI=2, when accuracy of better than 20% in LAI determination is required for reasonable accuracy in transpiration prediction. Similar variations in the relationship of GDD to LAI for corn crops grown in different years and on different soils were found by Dwyer and Stewart (1986). The large variability in estimated LAI, particularly during the early stages of crop development, make this relationship inappropriate for use in conjunction with our transpiration model.

Figure 12 shows the relationship of LAI to measured crop height for three growth periods (two in 1996 and one in 1995), and both treatments. In contrast with the GDD correlation, this correlation is very good during the initial stages of crop development, and less so later on. When considering that the requirements for accuracy of LAI determination decrease with increasing LAI, this correlation is well suited to use with the model.

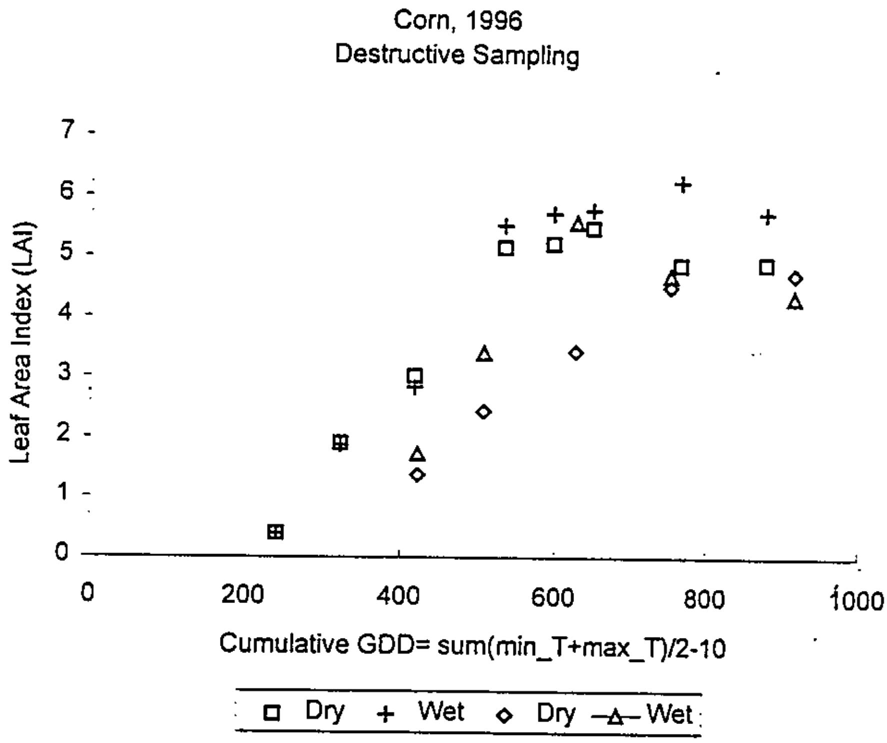


Figure 11. Leaf area index development as a function of growing degree day index (GDD) for the crops grown in the two irrigation treatments in 1996. LAI was measured destructively at least once a week and intermediate values were interpolated.

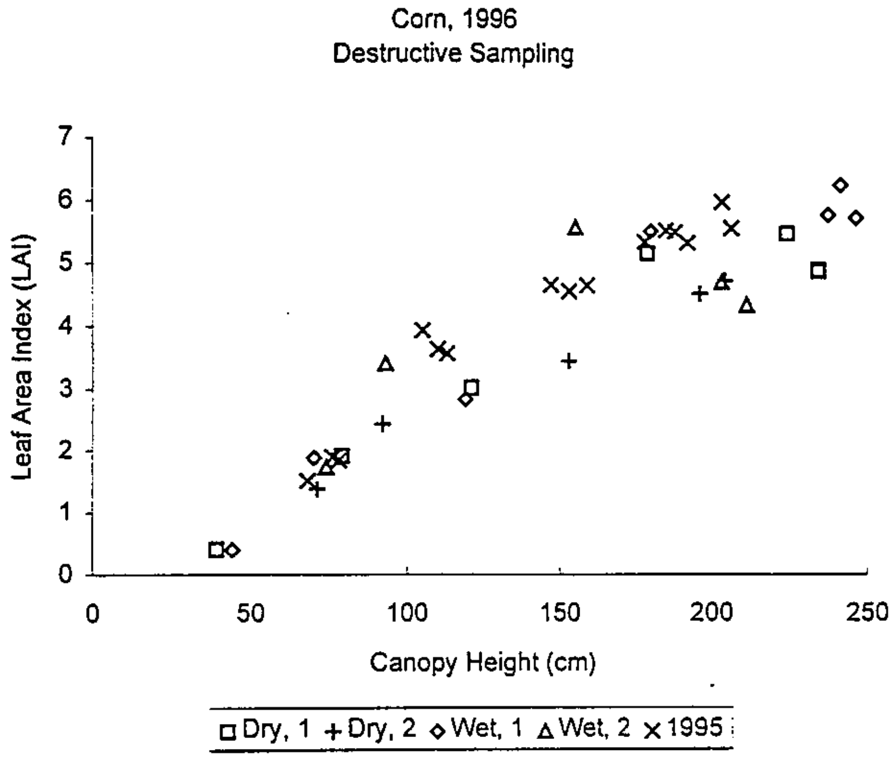


Figure 12. Leaf area index development as related to measured crop height for the crops grown in the two irrigation treatments in 1996 and for the crop grown in 1995.

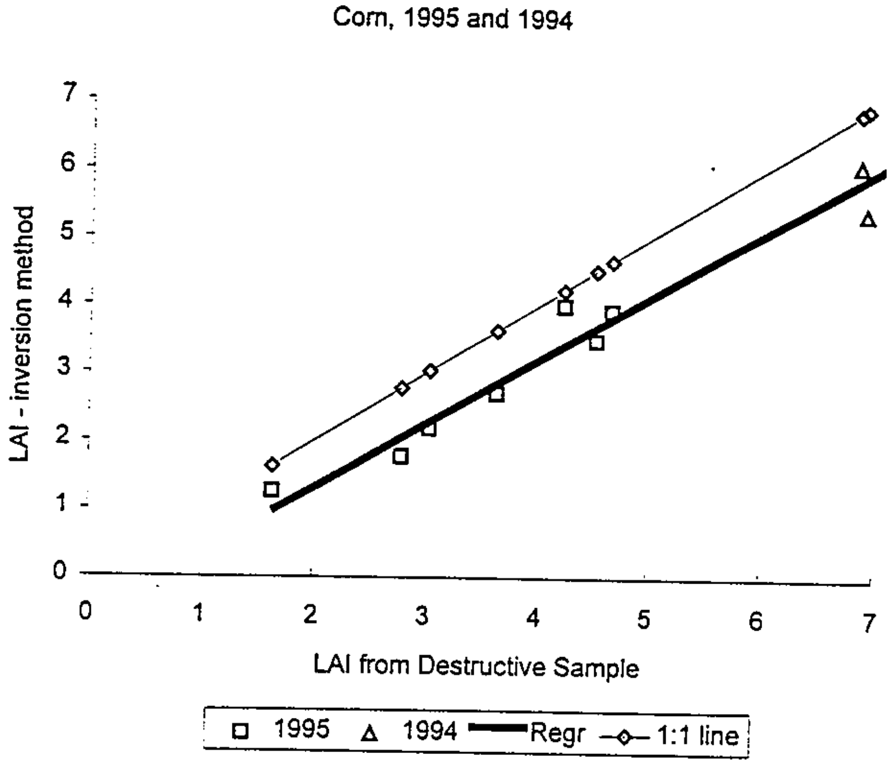


Figure 13. The relationship of leaf area index measured by the gap fraction inversion method to leaf area index measured destructively. Data are from 1994 and 1995.

Figure 13 shows the relationship of LAI measured with the inversion method to the destructive measurements of LAI. As generally reported for this technique, it underestimates LAI by approximately 20%. However, the figure hints that the relative accuracy may be slightly less for low LAI values. Many investigators of this technique recommend calibration for increased accuracy. This is relatively simple because the relationship of inversion estimates to actual LAI has been shown repeatedly to be linear.

In summary, an analysis of the sensitivity of transpiration to the various inputs shows clearly that the most important one is LAI. The requirement for LAI accuracy is highest when LAI is low (<4), especially between 1 and 2. Three methods for determining LAI were investigated: GDD index, correlation with height, and the gap fraction inversion method. GDD index is inaccurate for low LAI, and therefore does not meet the requirements. The relationship of LAI to crop height is promising, as it is most accurate at low LAI, when the best accuracy is required. There are two problems with using this correlation. Firstly, it is crop specific, and therefore will need calibration for each crop, planting distance and density. Secondly it will only work for field crops with a vertical habit (e.g. corn, wheat, sorghum and cotton), while for prostrate crops (e.g. melons, potatoes and tomatoes) and for orchard crops, it is not likely to be useful. Our results with gap fraction inversion, together with those reported by other workers (for review see Welles and Cohen, 1996) indicate that this method will be useful as it can give 20% accuracy. However, for low LAI (LAI<2) this will give an inaccuracy of >10% in computed transpiration. For cases where nothing better is practical (e.g. for orchard crops) this technique is our only choice. Since the accuracy of gap fraction inversion methods depends on the development of good measurement protocols (e.g. Cohen et. al., 1997), this study shows the importance of developing protocols for accurate LAI determination.

References:

Brutsaert W. 1982. Evaporation into the Atmosphere: theory, history and applications. Dordrecht: D. Reidel Publishing Co.

Campbell GS. 1977. An introduction to environmental biophysics. New York: Springer-Verlag.

Campbell, G. S. 1986. Extinction coefficients for radiation in plant canopies calculated using an ellipsoidal inclination angle distribution. Agricultural and Forest meteorology 36:317-321.

Cohen S., Sudhakara Rao R., Cohen Y. 1997. Canopy transmittance inversion using a line quantum probe for a row crop. Agricultural and Forest Meteorology (in press).

Cohen Y. 1994. Thermoelectric methods for measurement of sap flow in plants. Advances in Bioclimatology 3, 63-89

Cohen Y, Li Y. 1996. Validating sap flow measurement in field-grown sunflower and corn. Journal of Experimental Botany 47(304):1699-1707

Cohen Y, Plaut Z, Meiri A, Hadas A. 1995. Deficit irrigation of cotton for increasing groundwater use in clay soils. Agronomy Journal 87, 808-14.

Doorenbos, J. and Pruitt, W. O. 1975, Crop Water Requirements. Rome, FAO. p. 1-179.

Dwyer LM and Stewart DW 1986. Leaf area development in field-grown Maize. Agronomy Journal 78:334-43.

Fuchs M, Cohen Y, Moreshet S. 1987. Determining transpiration from meteorological data and crop characteristics for irrigation management. Irrigation Science 8, 91-9.

Hill, R. W. 1991. Irrigation scheduling. Agronomy Monographs, 31: 491-509.

Jones HG. 1992. Plants and Microclimate. A quantitative approach to environmental plant physiology. 2nd ed. Cambridge: Cambridge University Press.

Monteith JL. 1973. Principles of environmental physics. London: Edward Arnold.

Monteith, J. L. 1965. Evaporation and environment. in Fogg, G. E. The State and Movement of Water in Living Organisms. Cambridge University Press, Cambridge. p. 205-234.

Paltridge GW and Platt CMR. 1976. Radiative Processes in Meteorology and Climatology. N.Y. Elsevier. 318 pp.

Petersen, K. L., Fuchs, M., Moreshet, S., Cohen, Y., and Sinoquet, H. 1992. Computing transpiration of sunlit and shaded cotton foliage under variable water stress. Agronomy Journal 84:91-97.

Ross J. 1981. The Radiation Regime and Architecture of Plant Stands. W. Junk, The Hague. 391 pp.

Saugier B., Katerji N. 1991. Some plant factors controlling evapotranspiration. Agricultural and Forest meteorology 54:263-277.

Welles JM, Cohen S. 1996. Canopy structure measurement by gap fraction analysis using commercial instrumentation. Journal of Experimental Botany, 47:1335-42.

תקציר מונחה:

1. מטרות המחקר לתקופת הדו"ח תוך התייחסות לתוכנית העבודה.

להגדיר קריטריונים להשקיה המבוססים על יכולת בית השורשים לקלוט מים שקצב צריכתם ע"י הצמחים מבוקר ע"י הדרישה האטמוספרית להתאדות וע"י תגובות הצמח לתנאי עקת מים, ובנוסף לבחון כלים ושיטות לניתור מצב מים בצמח ובקרקע ואומדן היקף הנוף כדי ליישמם באופן מעשי בבקרת השקיה בשדה.

2. עיקרי הניסויים והתוצאות שהוגשו בתקופה אליה מתייחס הדו"ח.

הניסויים נעשו בשנים 1995, 1996 ו1997- בשדות תירס שגודלו בשני מחזורים. המדידות כללו את כל מה שתואר בתוכנית המחקר.

3. המסקנות המדעיות וההשלכות לגבי יישום המחקר והמשכו.

א. המודל לטרנספירציה מעריך נכון את צריכת המים של התירס. לכן ייתכן שבקרוב נפיץ מודל שימושי לקביעת תצרוכת מים לתירס ומספר גידולים נוספים על בסיס נתונים מטאורולוגיים ופרמטרים גיאומטריים המתארים את הגידול. ב. ניתן לקבוע מדד שטח עלים בשיטות של היפוך מדידות אור. בגידולים כמו תירס הקשר בין גובה העלווה למש"ע מתאים לשימוש במודל טרנספירציה.

4. הבעיות שנותרו לפתרון ו\או השינויים במהלך העבודה, התייחסות המשך המחקר לגביהם.

מחקר זה הגיע להישגים נאותים לגבי גידולי שדה טיפוסיים הדומים לצמח המודל, תירס. לגבי צמחים בעלי מבנה נוף יותר מורכב, כגון חמניות, או לגבי מטעים דרוש מחקר נוסף, שכבר הותחל במסגרת של פרוייקטים אחרים.

5. האם הוחל כבר בהפצת הידע שנוצר בתקופת הדו"ח:

כן. מאמר בעיתון Agricultural and Forest Meteorology . מאמר שני הוגש בכנס בשדה בוקר (ואולי יתפרסם ב-PROCEEDINGS). מאמר שלישי בהכנה. ראה נספחים לדו"ח.