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BARD

FINAL REPORT

PROJECT NO. I-944-85

Irrigation Scheduling of Orchards Based on Direct Measurements of Transpiration

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Standard BARD Cover Page for Scientific Reports

Date: November 18th, 1990

BARD
P.O. BOX 6
Bet Dagan, ISRAEL

BARD project No. I-944-85

Title

IRRIGATION SCHEDULING OF ORCHARDS BASED ON DIRECT

MEASUREMENTS OF TRANSPIRATION

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Project's starting date: FEBRUARY, 1987

Type of Report: 1st Annual _____ 2nd Annual _____ Final XXX

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$\frac{630.72}{\text{BAR/COH}}$; 634.3 : 631.7 : 581.129
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ABSTRACT

A three year study of grapefruit orchard water requirement was conducted in Israel for improving irrigation management. Transpiration rate was followed in a three group of eight trees each, using an automated system for measurement of sap flow in the trunk. The trees were selected to represent an orchard of about 0.8 ha, using canopy size and fruit yield as criterions. Global radiation, wind speed, temperature and humidity, were recorded automatically, the meteorological input together with orchard characteristics were used to compute the potential transpiration. In addition, soil water content, main root zone, xylem water potential, stomatal resistance, and fruit yield were determined occasionally.

Comparison of tranpiration, computed by a model with that measured by the sap flow, yielded good agreement. However, in the major part of the study, the model was used to estimate potential transpiraton (PTr) with the assumption of zero stomatal resistance. This parameter together with measured orchard transpiration by sap flow (Tr) were used for evaluatin of orchard response to climatic conditions and soil water availability. Tr was linearly related to PTr within a range up to 13 mm day^{-1} of PTr. Tr found to be sensitive to soil water availability and dropped short time (3 days) after the irrigation application. This drop in tranpiration rate during the irrigation interval commonly has not been coinsidered in the irrigation recommendations based on empirical parmeters. The results were an excessive water given for recharge of the soil and leaching problems. During one irrigation season, the irrigation of half of the orchard was scheduled by monitoring the transpiration. The

result was a reduction of water application from 3.3 mm day^{-1} in the whole orchard to 2.81 mm day^{-1} in the plot in which Tr was monitored. Yield was highly correlated with tranpiration rate, total yield and fruit size were not affected by monitoring the irrigation.

OBJECTIVES OF THE ORIGINAL RESEARCH PROPOSAL

Estimate orchard transpiration from measurement of representative number of trees using the heat pulse method.

Relate daily or periodically rate of water loss to environmental variables, and fruit productivity.

Develop an index to characterize the onset of tree water stress from the relationship between transpiration rate and xylem water potential.

Adding the orchard water requirement as an on-line input for controlling irrigation system.

1. DETERMINATION OF ORCHARD WATER REQUIREMENT BY A COMBINED TRUNK SAP FLOW AND METEOROLOGICAL APPROACH

ABSTRACT

Orchard water requirement was determined during two irrigation seasons using sap flow measurements in the trunk and potential transpiration computed from meteorological data. No treatments were applied other than to two trees which were irrigated every 3 days to maintain unlimited soil water availability and used as reference trees. Soil water potential was determined using neutron probes and moisture release curves. Potential transpiration was linearly related to measured transpiration. The ratio between the two was 0.3 under unlimited soil water availability. This ratio increased from August and reached values above 0.4 in late October. During a 14 day interval between irrigations in midsummer, the soil water potential in the main root zone dropped to -90 KPa and the ratio of transpiration to potential transpiration dropped to approximately 0.2. Average transpiration rate during midsummer was 2.5 mmd^{-1} . Water loss measured by soil water depletion was always lower than measured transpiration plus evaporation. Yield of individual trees was highly correlated with transpiration rate. Analysis of variability in transpiration between trees led to the conclusion that orchard transpiration may be determined with acceptable accuracy if sap flow is followed in at least 15 trees in the orchard.

INTRODUCTION

Progress in automatization of meteorological measurements and irrigation systems has made irrigation scheduling based on a formula estimating evapotranspiration from climatic data increasingly appealing. The major inconsistency in most climatic formula is the crop coefficient, which is determined empirically (Doorenbos and Pruitt, 1977) and is subject to variations caused by environmental conditions and growth (Jagtap and Jones, 1989). In a mature orchard with established irrigation management and almost constant soil cover by the canopy, the crop coefficient is affected mainly by a soil water regime and by variation in stomatal conductance due to physiological stage or seasonal effects (Phene et al., 1985; Hanks, 1985; Pruitt et al., 1972).

Water requirements of a whole citrus orchard have been studied using soil water balance (Bielorai, 1982) or combined with a meteorological approach (Kalma and Stanhill, 1969), while the evapotranspiration of single trees has been studied using lysimeters (Green and Moreshet 1979; du Plessis, 1985). Actual transpiration was computed in these studies on a long-term basis (weeks or months), and for this reason the more immediate response of the trees to soil water deficit or climatic parameters remains unknown. Determining tree response to its environment on the basis of a short period (days) is crucial for improvement of irrigation management. This is particularly important when wetted soil volume becomes limited due to the introduction of new irrigation technologies.

Priestly and Taylor (1972) suggested that there may be a range of soil water content for which the ratio of actual to potential transpiration

remains close to its maximum value. The ratio of evapotranspiration to pan evaporation in citrus has been shown to vary over a wide range (du Plessis, 1985), but no information was given to explain the inconsistency in its value. Seasonal changes in the ratio, mostly determined indirectly, were explained by variations in canopy resistance (Stanhill, 1972). The use of direct measurement of transpiration would allow determination of the ratio while avoiding the use of empirical equations for computation of canopy resistance.

The objectives of this study were to relate transpiration of single trees to potential transpiration computed from meteorological data and to examine the effect of soil water regime and atmospheric evaporative demand on the above ratio. Another objective of the study was to use the information on actual transpiration for irrigation scheduling of the orchard.

MATERIALS AND METHODS

The measurements were carried out in a 17-year-old grapefruit orchard on a sandy soil near Bet Dagan, Israel ($32^{\circ} 01'N$, $34^{\circ} 50'E$, 25m above MSL). The trees were of the Marsh Seedless variety grafted on sour orange rootstock. The experimental area was 0.76 ha, with 323 trees spaced 5.7m x 4m apart. The plot was surrounded by an approximately 30 ha citrus orchard. The plot was irrigated by minisprinklers emitting $160 \text{ dm}^3 \text{ h}^{-1}$ located at the row center, one sprinkler between every two trees. The leaf area index (LAI) of the canopy was estimated to be 5.5, and covered approximately 80% of the ground area. The climate is typically Mediterranean with a dry summer and rainy winter (535mm average annual rainfall). Maximum tree height was 5.0m.

The soil was sampled for mechanical analysis at 14 points. At the 0-60cm depth the soil is 85% sand, between 60 and 130 cm the clay and silt proportion varied from 22 to 55%.

Volumetric water content at field capacity was approximately 11, 14 and 15% at soil depths of 0-30, 30-60 and 90-120 cm, respectively; below this depth it was at least 17%. A moisture release curve of an undisturbed soil sample was determined using the procedure described by Moreshet et al. (1983).

Irrigation during 1988 was scheduled using the fixed tables distributed by the Ministry of Agriculture and based on Class A pan evaporation coefficients. Irrigation was applied at constant intervals of 14 days. For the irrigation season in 1989, the experimental plot was divided into two parts: 0.4 ha of the plot, in which irrigation (timing and amount) was

controlled by the measured transpiration rate of selected trees, and the rest of the area which was irrigated using the fixed tables.

Transpiration was measured by the heat pulse calibrated method (Cohen et al., 1981). For measurement of a single tree 7.5 minutes is required: eight trees were measured at hourly intervals for 24 hours a day. Measurements were automated under the control of CR-21X data logger (Campbell Scientific, Logan, UT, USA). A custom-made multiplexer enabled distribution of the heat pulse and scanning of the heat dissipation. Three sets of probes were placed in three orientations of the trunk of each of the selected trees. Flux measurements were taken at the three orientations during several days to determine the ratio of the sap flow among the three orientations; for routine measurements only one of the probes was used, and the sap flow values were corrected according to the above ratio. In general the ratio among three sets of probes in one tree ranged between 0.9 and 1.1. The diurnal differences in the ratio may be ignored. During the first year (1988) sap flow was measured on 14 trees, two of which were irrigated every 3 days to maintain unlimited soil water conditions; these two trees were used as reference. In 1989, eight trees were added to the sample. Global radiation, wind speed, temperature and humidity were averaged for 7.5-min periods and recorded automatically using a data logger (CR-7 Campbell Scientific). The meteorological input together with orchard characteristics (height, row spacing, leaf diameter, LAI) were used to compute the potential transpiration using the Penman Monteith linear model as described by Fuchs et al. (1987), assuming zero canopy resistance.

For measurement of soil water content a neutron probe was used, with 80 aluminium access tubes placed 1.5m deep, in the area of four trees of about 20m² each (20 tubes per tree). Measurements were taken during the first year of the experiment at 2-day intervals..

Fruit yield was determined for each of the selected trees. Samples of 100-150 fruits were weighed separately to determine fruit size.

RESULTS

Potential transpiration (PTr) from the orchards, computed by the model, was proportional to pan evaporation (pa) data taken from an open site, located about 3 km distant from the orchard. The regression equation for 50 daily values of PTr and pa was: $PTr = 1.28 pa$. The model for PTr considers the roughness of the canopy in the orchard, and therefore the computed values of PTr are higher than the pa data. Analysis of the results in the following sections of this study is based on the computed PTr only.

A typical diurnal curve of hourly transpiration (Tr) values is given in Figure 1 for 2 days with equal potential transpiration and different soil water content. Therefore, the difference in Tr was caused by soil water availability only. Immediately after the irrigation, the Tr diurnal curve followed the diurnal trend of solar radiation flux, but 13 days after irrigation Tr dropped and the diurnal curve deviated slightly from the previous pattern. Daily Tr was obtained by summing the hourly values. Data during the night were not included, because of the limited accuracy of the method at flows slower than 0.5 l h^{-1} . The daily Tr showed a reduction of nearly 30% after 13 days of soil drying.

Potential transpiration was linearly related to daily values of measured transpiration. The regression in Figure 2 is based on data taken from the two reference trees (not limited by soil water availability) for several days with a wide range of Tr rate caused by different atmospheric evaporative demands. The high correlation coefficient obtained under unlimited water availability validates the use of the ratio Tr/PTr to indicate a drop in Tr resulted from a drop in soil water availability.

Fig. 1: Diurnal curve of measured transpiration rate in a single tree. Potential transpiration was 9.1 and 9.0 mm d⁻¹ for 1 and 13 days after irrigation, respectively.

Fig. 2: Linear regression between measured and potential transpiration. An average of two trees which were irrigated every 3 days to maintain unlimited soil water availability.

A typical response of Tr during an irrigation interval is shown in Figure 3. The data in the figure are an average of six trees. Large variations in PTr occurred during the first 4 days of the interval and were completely reflected by the daily Tr , and therefore the ratio Tr/PTr remained almost constant for the first 4 days. The slight drop in the ratio on the second day of the interval (180) shows that under extremely high evaporative demands, Tr does not increase proportionally with PTr . The ratio dropped from 0.29 on the first day after irrigation to 0.21 on the last day of the interval. This is a reduction of 28%, presumably resulting from the drop in soil water content. Total transpiration for the whole cycle was 32.2 mm, or an average Tr of 2.5 mm d^{-1} .

Soil water potential at the 0-60cm depth during the irrigation interval decreased to -90 KPa and in the deeper soil layers the reduction of soil water potential was almost unmeasurable. The accumulated soil water loss from the soil, as determined by the neutron probe, was lower than the amount of water computed by sap flow measurements. During the irrigation interval described above, the accumulated soil water loss at the end of the interval was 80, 66, 59 and 43% of the Tr , respectively, for the four trees in which soil water content was determined. Water loss from the soil presumably includes evaporation as well as transpiration. The unreasonable results obtained in these measurements reflect the difficulty in using the neutron probe method for soil water balance studies.

The ratio Tr/PTr on the first day of the irrigation interval (Tr_i/PTr_i) throughout the irrigation season was nearly steady until approximately Julian day 200 and then increased gradually (Fig. 4). Each point on the

Fig. 3: Potential transpiration (A), measured transpiration (B) and the ratio between them (C). Irrigation was applied on Julian day 178. Values of measured transpiration are an average of six trees.

Fig. 4: Ratio of measured to potential transpiration at the beginning of the irrigation interval ($Tr/pTri$) and at the end of the interval ($Tre/pTre$). Nine intervals are shown throughout the irrigation season in 1988.

curve is an average of six trees. The ratio on the last day of an irrigation interval (T_r/pT_r) was lower than at the beginning and indicates the drop in T_r after soil drying. T_r/pT_r expressed as a percentage of T_{ri}/pT_{ri} is given in Figure 5 for two irrigation seasons. In 1988 there was no intervention in the farm irrigation management (14 days between irrigations), but in 1989 irrigation was scheduled using the output of daily T_r data. An arbitrary decision was taken in 1989 to permit reduction in the percentage to a level not lower than 80; T_r and pT_r were followed daily, and when the percentage approached 80 the orchard was irrigated. The amount of water applied was set as the daily accumulated T_r from the last irrigation augmented by 20% to account for evaporation from the soil.

Total amount of applied water during the two irrigation seasons and its distribution are shown in Figure 6. In 1988 the average for the entire irrigation season was 3.33 mm d^{-1} . In 1989, the amount of water was reduced to an average of 3.09 mm d^{-1} . In the plot in which T_r was monitored the average water application was 2.81 mm d^{-1} .

Yield as related to yearly rate of transpiration for each of the selected trees is given in Figure 7. During April to November, missing T_r data were completed by extrapolation from the previous day or previous irrigation interval. During December to March (winter season) pT_r was computed every day and that value plus the ratio T_r/pT_r in November, were used to compute transpiration rate. The yield of the individual trees in both seasons was highly correlated with transpiration rate. Total yield averaged from the sampled trees (82 Mg ha^{-1}), and fruit size were not affected by monitoring

Fig. 5: Ratio of measured to potential transpiration at the end of the irrigation interval ($Tre/pTre$) expressed as percentage of the ratio at the beginning of the interval ($Tri/pTri$). Nine intervals are shown throughout the irrigation season in 1988.

Fig. 6: Amount of water applied for each irrigation interval throughout 1988 and 1989. (Monitored = plot irrigated using sap flow measurement as the criterion.)

Fig. 7: Relationship of yield and yearly accumulated transpiration for individual trees. (Monitored = trees in plot irrigated using sap flow measurement as the criterion.)

the irrigation in 1989. The large range in the yield of the sampled trees indicates large variability between trees.

Variability in transpiration between trees is also an important factor to be considered when orchard transpiration is estimated from measurements of a few sampled trees. In the present orchard, the standard deviation of 22 sampled trees (in July 1989) was high (Fig .8). The figure shows that number of sampled trees must be high for reasonable accuracy of orchard transpiration. For example, 15 trees should be sampled in order to estimate orchard transpiration with an error of 7 l d^{-1} (10% of the mean).

Fig. 8: Number of trees required at 95% confidence limit, so that estimation of orchard transpiration is off by e (expressed in l d^{-1}) from the mean sample. Mean transpiration for 22 trees = 70.3 l d^{-1} ; $\text{SD} = 14.44$. (Data were normalized with respect to the reference trees.)

DISCUSSION

Average transpiration rate from April until October varied from nearly 40 to 95 l d^{-1} for different trees under unlimited soil water supply. These values are comparable to evapotranspiration values of 65-90 l d^{-1} obtained in a lysimeter study with 16-year-old Valencia trees and a LAI similar to that of the grapefruit in this study (du Plessis, 1985). The average rate of 2.5 mm d^{-1} which was measured during an irrigation interval in July is approximately 0.5 mm higher than the transpiration rate estimated from soil water balance in a 35-year-old Shamouti orange orchard (Kalma and Stanhill, 1969). Using the measured transpiration data in the present study as the criterion for water application, without any resultant physiological stress during the season and without reducing yield, indicates that the computed values are realistic or, at the very least, not underestimated.

Direct evaporation from the soil surface was not measured for lack of a reliable method of measurement. In a study with a clay loam soil, an average value of 0.7 mm d^{-1} immediately after irrigation during July and August was reported (Kalma and Stanhill, 1969). The top 30- cm soil layer in the present study is mostly sand, and therefore evaporation from the wet surface is expected to be less than that found on the heavier soil, and the rate would drop markedly 2 or 3 days after irrigation (Monteith, 1981). Evaporation during July and August was estimated to be approximately 0.5 mm d^{-1} for the entire irrigation interval. This is 20% of the transpiration rate measured in this period (average of 2.5 mm d^{-1}).

Evapotranspiration compared with the amount of applied water is given in Table 1. The differences were integrated for the whole irrigation interval in order to obtain the total amount of water drained below the root zone during each interval. For the period specified in Table 1 (164 days), total drained water was 90.2 mm. The irrigation is generally extended to 200 days and therefore loss of water may increase accordingly.

Potential transpiration was linearly related to the measured transpiration and the ratio Tr/pTr remained constant. This was demonstrated in the reference trees and also in all trees during the first 3 days after irrigation. An exception is shown in Figure 3, for when pTr was greater than 13 mm d^{-1} and the ratio Tr/pTr dropped by approximately 0.02. It is not clear whether this drop in the ratio is a temporary response caused by a delay in stomatal adaptation to the extreme evaporative demands, or is the result of an upper limit of transpiration rate by the trees.

Linearity between evapotranspiration from citrus and potential evaporation has also been reported in other studies (du Plessis, 1985; van Bavel, 1967). However, the slope of the relationship in those studies and also in the present study was not constant throughout the year, suggesting seasonal variations in canopy resistance.

Under drying soil, Tr/pTr ratio was no longer a constant ratio, but dropped with decreasing soil water content. This drop in the ratio may be used as a parameter for irrigation scheduling. Presently, little is known as to the extent to which the drop in Tr/pTr ratio affects growth and yield. It is generally accepted that the ratio Tr/pTr should be close to its maximum level, since dry matter production is linearly related to transpiration.

Table 1. Evapotranspiration, water application and water drained through the root zone in the 1988 irrigation season.

Julian day	Average ET (mm d ⁻¹)	Water supply (mm d ⁻¹)	Integrated amount of drained water mm
124	2.81	3.0	2.7
138	2.93	3.0	0.9
165	2.94	3.0	0.8
193	3.02	3.62	16.6
207	3.06	3.62	7.9
236	2.91	3.62	18.8
250	2.81	3.38	9.0
282	2.44	3.38	26.2
288	2.32	2.58	7.3
Total			90.2

This relationship has been widely demonstrated in crops, but in fruit trees it was found complicated. Furthermore, there was evidence that transpiration in citrus trees does not correlate with yield (Kriedemann and Barrs, 1981). The high correlation between yield and accumulated transpiration (Fig. 7) is an important finding which was not reported earlier. This correlation does not necessarily contradict conclusions in other studies that wide differences in total water supply resulted in a similar yield (Hilgeman and Sharp, 1970). Most earlier studies correlated yield with water applications or with soil water depletion, but the water fraction used for transpiration was unknown or indirectly estimated. The works with lysimeters are the exception (du Plessis, 1985; Green and Moreshet, 1979), but in those studies only one to three trees were measured and therefore the correlation between transpiration and yield was limited.

Variability among trees is expected, due to genetic heterogeneity, soil spatial variability, non-uniformity of irrigation, and pruning. These above factors suggest that the variability in transpiration found in this orchard is not likely to be generally applicable. Error in measurement of sap flow is another factor contributing to the variability among trees; this source of error was dealt with in an earlier study (Cohen et al., 1981) and was estimated to be $\pm 5\%$. Based on the variability found for this orchard, it is assumed that reasonable accuracy in determination of orchard transpiration can be achieved if 15 trees are selected for a preliminary study of the variability. At a later stage, for routine measurements, the number of selected trees may be reduced considering the accuracy required by the measurement.

2. ESTIMATING CITRUS ORCHARD CANOPY RESISTANCE FROM MEASUREMENT OF ACTUAL AND POTENTIAL TRANSPIRATION

INTRODUCTION

Accurate interpretation of orchard transpiration obtained by sap flow measurements is difficult if environmental variables are not considered. Water use by a tree depends upon atmospheric evaporative demand and upon soil water availability. For a given set of environmental conditions, transpiration rates from two different levels of soil water availability vary considerably. On other hand, under equal soil water availability, transpiration rate may be considerably different under various atmospheric evaporative demands. By studying plant-environment-transpiration interaction, the response of the orchard to environmental variable can better be estimated. This interaction may be studied by the relationship between actual orchard transpiration and estimated potential transpiration by a model.

The potential transpiration concept which integrates the effect of climatic factors on transpiration was used in this study. The model for potential transpiration is based on Penman linear Model but takes into account the canopy structure, the leaf Area Index and the resistance of the canopy to diffusion of water vapor (Fuchs et al. 1987). Of all the factors involved in the computation of potential transpiration, the resistance of the canopy to vapor diffusion is the most difficult to characterize. This resistance depends on the stomatal aperture which is controlled by the water status, therefore it is indirectly related to the soil water availability.

Stomatal aperture is also related to photo-synthetic waveband of solar radiation and surface leaf temperature. In orchards, analysis of canopy light interception is more complicated than in field crops (Ross, 1981). Other factor which may complicate the computation of canopy resistance in trees is the variation in leaf resistance due to leaf age, physiological stage and water vapor gradient Camacho-B, 1977; Meyer and Green, 1981).

An attempt to estimate orchard canopy resistance was made in this study during two days when soil water availability was not limited. Intensive measurements of leaf stomatal resistance, sap flow, in the trunk and climatic factors for the model input, were determined.

MATERIALS AND METHODS

The site of the experiment, characteristics of the canopy and detailed description of the application of the heat pulse technique in the trees were given in Part 1 of this report. An automatic meteorological station was operated throughout the entire irrigation period from March to April during two experimental seasons. Global radiation (Kipp and Zonen, Delft, Netherlands), wind speed and direction (Model 014A and 024A met-one, Sunnyvale, CA, USA), temperature and humidity (Model 201 Campbell Scientific Logan, UT, USA) were collected every 7.5 minutes and recorded (CR-7 Campbell Scientific). Additional input to the model were the following canopy parameters: Canopy height was measured at three points for each location (at the center of the trunk row and 1.5m distance from the trunk row at each side). Row width was measured in three points along the sampled location. Leaf Area Index (LAI) was estimated. For the two days test of orchard

canopy resistance, stomatal resistance was measured at hourly intervals, repeatedly in a set of 48 selected leaves. Two model LI 1600 steady state porometers (Licor, Lincoln, NE, USA) were used. Twelve leaves were selected along approximately 5 m of the row in 4 locations as follows:

Upper 1.5 m layer in the east side of the row (top east).

Upper 1.5 m layer in the west side of the row (top west).

1.5 to 3.5 m from the top in the east side of the row (bottom east)

1.5 to 3.5 m from the top in the west side of the row (bottom west)

Stomatal resistance, leaf temperature and Photosynthetic Active Radiation (PAR) on the measured leaf surface were automatically recorded from the porometer.

RESULTS AND DISCUSSION

A sensitivity analysis of the model for computation of potential transpiration made for cotton, demonstrated the dominant effect of stomatal resistance on transpiration (Fuchs, 1986). Fig. 9 shows the computed transpiration in citrus as a function of stomatal resistance (other climatic inputs to the model were considered constant and selected to be typical for noon hours of summer day in the coastal region of Israel). Distribution of the canopy between sunlit and shaded leaves has not been analyzed as described in the model (Fuchs et al., 1987). One of the main reasons for not considering the distribution between the two types of leaves is lack of an accurate technique or a simple model to analyze it in orchards. It will

Fig. 9: Computed transpiration rate as a function of canopy resistance. All climatic inputs to the model were considered constant.

be shown later that in citrus differences in stomatal resistance between sunlit and shaded leaves are difficult to be defined.

The figure shows that transpiration is sensitive to change of canopy resistance between 0 to about 400 s m⁻². An accurate use of the model requires a mathematical function relating stomatal resistance of citrus orchard to environmental factors, this function has not been studied yet.

An intensive effort to determine orchard canopy resistance and to examine the stomatal response to photosynthetic flux density was made in this study under unlimited soil water availability. Figure 10 shows the diurnal change in stomatal conductance of 12 leaves in the eastern side of the row on the top part of the canopy. This part of the canopy is exposed to radiation during a large proportion of the daylight hours. Excluding the set of measurements which was taken at about 0900 in the morning there were only slight changes in stomatal conductance during the day. Values of the conductance are considerably lower compared to other species (Denmead and Miller, 1976; Meyer and Green, 1981), but they are comparable with data found in earlier studies in citrus (Camacho-B, 1977; Levy and Kaufmann, 1976). Similar tendency of diurnal curve of the stomatal conductance is shown for the bottom part of the canopy at the same row side (Fig. 11), stomatal conductance on 0900 and 1000 hr are relatively high and were dropped sharply during the rest of the day. Stomatal conductance at the west side of the row (top and bottom) were low for the entire day.

Since the west side is not exposed to radiation during the early morning hours, stomatal conductance during the morning was not different (or even lower) compared to that measured during the rest of the day (Figs. 12 and 13).

Fig. 10: Diurnal curve of leaf stomatal conductance in the top east side of the canopy, every point presents a single leaf.

Fig. 11: Diurnal curve of leaf stomatal conductance in the bottom east side of the canopy, every point presents a single leaf.

Fig. 12: Diurnal curve of leaf stomatal conductance in the top west side of the canopy, every point presents a single leaf.

Fig. 13: Diurnal curve of leaf stomatal conductance in the bottom west side of the canopy, every point presents a single leaf.

Lack of diurnal response of stomatal conductance is reflected by poor relationship between stomatal conductance and PAR (Figs. 14-17). The high values of stomatal conductance at high range of PAR in the eastern side of the row (Figs. 14 and 15) present the morning hour values. However, excluding these morning values in the eastern side, it seems to be extremely difficult to find a correlation between stomatal conductance in citrus and radiative flux density during the day. These results may wrongly be interpreted as there is no effect of light on stomatal conductance in citrus. In fact, stomatal conductance in the morning hours at the eastern side of the row is closely related to radiative flux. Later, during the day, increasing atmospheric evaporative demands leads to higher rate of water loss from the leaf. Consequently leaf water potential reaches a low level in which stomata are closed. This response of stomata to leaf water status has already been described earlier (Levy and Kaufmann, 1976; Barrs and Klepper, 1968) and it has an important practical implications on water relation of citrus orchard.

Figure 18 shows the diurnal trend of canopy resistance in the measured trees. Values in the figure were obtained by averaging the stomatal resistance in the 4 measured locations and use LAI value of 5. As may be expected from the previous figures, the canopy resistance increased gradually during the day. Earlier than 0900 hr, porometer measurements were not allowed since the leaves were still wet by the dew. From 1700 afternoon, the resistance was high and accuracy of the measurements was low, therefore data were not collected. The model for estimating potential transpiration, which was applied for cotton plants, considers the functions relating leaf stomatal resistance to radiative flux (Fuchs et al., 1987).

Fig. 14: Leaf stomatal conductance as a function of PAR in the top east side of the canopy, every point presents a single leaf.

Fig. 15: Leaf stomatal conductance as a function of PAR in the bottom east side of the canopy, every point presents a single leaf.

Fig. 16: Leaf stomatal conductance as a function of PAR in the top west side of the canopy, every point presents a single leaf.

Fig. 17: Leaf stomatal conductance as a function of PAR in the bottom west side of the canopy, every point presents a single leaf.

Fig. 18: Change in canopy resistance as a function of time, values were calculated from the average of the leaf stomatal resistance taken in all directions, assuming LAI is 5.

Figs. 14 to 17 indicate that in citrus these functions are difficult to be defined and excluding the data in the morning hours there was hardly effect of radiative flux on stomatal resistance.

Transpiration rate, computed from climatic parameters, canopy characteristics and measured canopy resistance is compared with measured transpiration in Fig. 19. Measured transpiration values (sap flow) are an average of two trees in which stomatal resistance was measured. In the morning hours the transpiration rate is higher than the sap flow, suggesting internal water storage was used for transpiration. On afternoon hours, the transpiration diminished earlier than the sap flow since water still was taken for recovery of the internal storage. The close agreement between the two methods shows that intensive measurements of stomatal resistance in citrus orchard, allow an estimation of canopy resistance at acceptable accuracy.

Fig. 19: Comparison between diurnal curves of computed and measured transpiration, data were collected in Julian day 142, 1989.

3. EFFECT OF ENVIRONMENTAL FACTORS ON CITRUS CANOPY RESISTANCE

INTRODUCTION

The objective of this part of the project was to study the response of transpiration to variations in climatic factors. Stomatal resistance was not followed because of the intensive measurements required for determination of canopy resistance. In the following sections results from the computation of potential transpiration which will be presented, are all based on the assumption that canopy resistance equals zero, its actual value may be estimated by the ratio of transpiration rate (sap flow) measured by the heat pulse (Tr.) to the rate of potential transpiration computed by the model (Ptr).

RESULTS AND DISCUSSION

The potential transpiration, computed by the model, was linearly related to evaporation from by pan evaporation (Fig. 20). Data for pan evaporation (Pa) were taken from open site, located in the Institute of the Meteorological service, in Bet Dagan, about 3 km distance from the orchard. The figure shows about 50 daily values of potential transpiration and pan evaporation, the intercept of the regression line was 1.28, indicating overestimation of potential transpiration by the model compared to pan evaporation. The difference in estimation of potential evaporation between the two methods may be explained by the difference between the smooth water surface in the pan compared to the roughness of the canopy. The model

Fig. 20: Relationship between potential transpiration computed by the model (Canopy resistance assumed zero) and evaporation from class A pan.

considers the turbulent air flow through the canopy, therefore, it may potentially extract water vapor at a higher rate than from smooth water surface. Figure 21 shows the effect of atmospheric evaporative demands on measured and potential transpiration. The figure presents data which were collected during a period of 14 days, from Julian day 151 to 165, in trees which were irrigated at 3 days intervals (reference trees). Maintaining soil water availability at high level, eliminated the effect of soil water stress on transpiration. Atmospheric evaporative demands varied largely during the given period, minimum rate of PTr was about 7.5 mm day^{-1} and the maximum was nearly 13 mm day^{-1} (Fig. 21a). Fluctuation in PTr between the days was high, but it almost completely followed by the measured transpiration (Fig. 21b) and the ratio between the two remained nearly constant throughout the measurement period (fig. 21c). Transpiration data and Tr/PTr ratio are an average of two trees, the ratio was about 0.28 with insignificant fluctuation during the entire period. Since a value of zero canopy resistance was introduced into the computation of potential transpiration, it was overestimated by the model and therefore the ratio is below 1. However, the low ratio, which indicates high canopy resistance, is in accordance with the above data on canopy resistance which was shown to be very high during most times of the day.

Similar response of Tr/PTr to climate may be seen in Fig. 22, which presents data averaged for six trees which were irrigated at 14 days intervals. The first three days in Fig. 22 are specified by low soil water availability since the orchard was irrigated 11 days earlier (on Julian day 122). During these three days Tr/PTr was low (Fig. 22c) but it was similar for the three days irrespective of the large variations in potential

Fig. 21: Potential transpiration (A), measured transpiration (B) and the ratio between them (C). Irrigation was applied every 3 days, values of measured transpiration are average of two trees.

Fig. 22: Potential transpiration (A), measured transpiration (B) and the ratio between them (C). Irrigations were applied on Julian days 122 and 135, values of measured transpiration are an average of 6 trees.

transpiration (Fig. 22a). After the irrigation on the afternoon of day 135, the ratio increased significantly on days 136 and 137 but was identical irrespective of the high difference in potential transpiration between the two days. These data support the findings which were shown above for the two reference trees that climatic factors, within the given range of atmospheric evaporative demands, had no effect on Tr/PTr . The interpretation of these results is that under unlimited soil water availability canopy resistance does not limit transpiration within the measured range of evaporative demands. But when soil water content decreases, canopy resistance increases, therefore transpiration is limited.

The effect of drop in soil water availability on Tr/PTr of individual trees is shown in Fig. 23. Comparison is made between two days with the same potential transpiration rate. Twelve days after the irrigation, soil water potential, averaged for the upper 60 cm layer, dropped to -80 KPa, consequently transpiration rate dropped and Tr/PTr , averaged for trees 1 to 6 dropped by 28%. The ratio at the first day after irrigation varied from 0.27 to 0.34 and the drop during the drying period varied from 19% to 39% of that at the first day after irrigation. Trees 7 and 8 are the reference trees which were irrigated at 3 days interval.

Tr/PTr calculated on hourly basis during a typical summer day when soil water availability is not limited is shown in Fig. 24. In the early morning hours the ratio is below 0.3, later during the noon hours it is about 0.3 and towards the afternoon hours it increased to a value close to 1. Although it has been shown so far that PTr is well correlated with Tr , Fig. 24 suggests that Tr (sap flow in the trunk) is not synchronized with potential transpiration on hourly basis. The curve may be interpreted in view of the

Fig. 23: Ratio of measured to potential transpiration of individual trees, 1 and 12 days following irrigation.

Fig. 24: Diurnal trend in Tr/PTr ratio, values of Tr are an average of 8 trees.

difference between transpiration (water loss to the atmosphere) and sap flow in the trunk. This difference has already been shown in Fig. 19, which compares potential to measured transpiration. In the early morning hours, sap flow in the trunk may be lagged behind the water loss through the canopy (which is proportional to potential transpiration). The lagging occurs because a fraction of water storage in the tree is lost through the canopy without being actually detected by the sap flow measurements. Therefore, the rate of the sap flow (Tr) is lower than rate of water loss and Tr/PTr is low. In the afternoon, sap flow rate would still be high, while water loss through the canopy drops with decreasing atmospheric evaporative demands. Therefore, the ratio Tr/PTr may be as high as close to unity.

Seasonal effect on Tr/PTr is shown in Table 2 for 4 days with different potential transpiration, but no limitation in soil water availability. On Julian days 179 and 180 (end of June), the ratio was close to 0.3 under moderate or extreme atmospheric evaporative demands. But about 100 days later (middle of October) the ratio was higher by nearly 50%. The seasonal trend in the ratio from April to November 1989 is shown in Fig. 25. A significant increase in the ratio may be noticed from late August.

The seasonal variations in Tr/PTr may be associated with internal changes in tree water transport system related to stage development of the tree. However, the physiological explanation of these changes is not yet understood.

JULIAN DAY	PT _r mm d ⁻¹	T _r mm d ⁻¹	T _r /PT _r
179	10.2	3.09(sd=0.34)	0.3
180	13.6	3.41(sd=0.35)	0.28
285	5.19	2.25(sd=0.21)	0.43
286	6.85	2.64(sd=0.23)	0.45

Table 2: Measured to potential transpiration ratio on different days during 1989.
Values for measured transpiration are an average of 8 trees.

Fig. 25: Seasonal trend in the ratio measured to potential transpiration, values of measured transpiration are an average of 8 trees.

4. DROP IN TRANSPIRATION RATE AND LEAF WATER POTENTIAL WITH SOIL DRYING

INTRODUCTION

Irrigation scheduling in many citrus orchards in Israel is based on pan evaporation data, which were collected in specific regions and corrected by empirical coefficients. Soil condition, orchard characteristics and daily variations in climatic conditions are completely ignored by the pan evaporation coefficient. In a little number of orchards depletion in soil water content or soil water potential is followed and irrigation applied accordingly, however, in orchards there is uncertainty in defining the main root zone, therefore, moisture sensors may be placed in locations which do not present the main root zone. None of the above two methods, which are largely used in orchards, considers the tree response to its environment, therefore the error in estimating the rate of water loss is sometimes considerably high. The objective in this part of the study was to relate water uptake by the tree and tree water status to soil water availability.

MATERIALS AND METHODS

Soil moisture: A neutron probe was used in four trees, the probe was separately calibrated for the layer of 0-0.3 m and for all the layers below this depth. Twenty access tubes were installed for each tree (1*1 m) to a depth of 1.5 m. Measurements were made every two days. Soil water

potential was determined from moisture release curve of an undisturbed soil sample, using a procedure which was described by Moreshet et al. (1983).

Leaf xylem water potential was measured with a pressure chamber (Arimad 2, Kfar Haroob, Israel) on fully exposed and deeply shaded leaves covered with aluminum foil one day before the measurements (three replicate of each). Transpiration measurement by the heat pulse method was described in part one of this report. Distribution of roots was tested in a 4 m long trench, perpendicular to the tree row line. The number of root tips was counted in a grid of rectangles of 0.1×0.1 m.

RESULTS AND DISCUSSION

Soil water content at different depths during an irrigation interval is shown in Fig. 26. Water capacity of the upper 0.6 m is low compare to deeper layers but high proportion of the root system was concentrated in this layer (Table 3). The major part of water was taken from this depth. Water uptake by the tree from depth 0.6 to 1.2 m was insignificant and from a depth below 1.2 m, there was no water uptake. The drop in soil water potential calculated for 0-0.6 m depth during three irrigation intervals is shown in Fig. 27. The rate of drop was strongly affected by time of the year. Early in the irrigation season (April), the rate of drop in soil water potential was lower than at the middle of the season. Data on transpiration rate which will later be presented showed that in the early spring, transpiration was limited by low atmospheric evaporative demands, therefore the drop in soil water potential was moderate. In the autumn, as

Table 3: Root density as a function of depth and distance from the tree row line. Data are presented as a percentage of total number of root tips in the trench in both east and west side of the row line.

Depth (m)	Distance from row line (m)			
	East		West	
	0-1	1-2	0-1	1-2
0 -0.1	9	13	6	8
0.1-0.2	3	5	4	6
0.2-0.3	4	7	4	4
0.3-0.4	2	1	2	1
0.4-0.5	3	2	4	1
0.5-0.6	2	3	2	1
0.6-0.7	0	1	2	0

Fig. 26: Soil water content at different soil layers during irrigation interval.

Fig. 27: Soil water potential at 0-0.6 m during three irrigation intervals.

in the early spring, transpiration rate also limited and the rate of drop in soil water potential was low.

The effect of soil water availability on transpiration is demonstrated for one single tree in Fig. 28. Potential transpiration (PTr) was similar in the two days, but soil water availability was high (one day after irrigation) on day 179 and low (12 days after irrigation) on day 190. In the morning hours, soil water stress had less effect on transpiration rate (Tr) than at noon and afternoon hours. Drop in transpiration rate as a result of soil drying was significant. Transpiration rate of individual trees at the beginning and the end of three irrigation intervals during the irrigation season is shown in Figs. 29-31. On April (irrigation on Julian day 108), the rate of transpiration, 13 days after the irrigation, was 10.5 % of the rate on the first day (Fig.29). Differences between trees were large in both, the absolute values of transpiration and the percentage of the drop in transpiration rate. Trees 7 and 8 were irrigated at 3 days intervals and used as reference trees. Analysis of the variability in transpiration rate between trees was made in the first part of this report. Figure 29 illustrates the problem with estimating orchard water requirement, based on data taken from single trees. With such a high variability between trees, sampling of the trees for accurate determination of orchard water requirement appear to be a serious problem.

Figure 30 presents similar data taken in other set of trees for irrigation interval on July (irrigation on Julian day 206). The average drop in transpiration rate 13 days after the irrigation was 28% compare to the first day. The drop in transpiration during irrigation cycle on October

Fig. 28: Effect of soil drying on transpiration rate, comparison is made between two days of similar potential transpiration but different soil water availability, irrigation was applied on Julian day 178.

Fig. 29: Transpiration rate of individual trees at the beginning and the end of irrigation interval, irrigation was applied on Julian day 108, trees 7 and 8 were irrigated every 3 days.

Fig. 30: Transpiration rate of individual trees at the beginning and the end of irrigation interval, irrigation was applied on Julian day 206, trees 7 and 8 were irrigated every 3 days.

(irrigation on Julian day 279) was 14% of the rate on the first day (Fig. 31). Absolute values of transpiration and variability between trees at this time of year were much lower than in the summer. Average transpiration rate of six trees during an irrigation interval in the summer normalized to the rate at the first day after irrigation is shown in Fig. 32. For the first three days after the irrigation, transpiration rate was not limited by soil water availability. Later it was steeply dropped for about 6 days, towards the end of the irrigation cycle the rate of drop was lower than earlier. The figure clearly shows that for this time of the season under the given soil characteristics, trees sense water stress very soon after the irrigation. This drop in transpiration rate during the irrigation cycle has two practical implications. First the effect of increasing canopy resistance on dry matter production and fruit development. Second is the accumulated computed water loss from the orchard for the entire irrigation interval. If, for instance, pan evaporation factor is used, the amount of water which may be added to discharge the soil is above the amount which actually lost from the soil.

Comparison between water loss by a tree, obtained from accumulated hourly values of transpiration rate and soil water depletion, measured every two days, was made during two irrigation intervals in four trees. This comparison was made in order to evaluate the relative accuracy of the two methods to estimate orchard water requirements. In all cases measurements of neutron probes underestimated water loss compare to direct measurements of transpiration. Figure 33 presents the accumulated water loss calculated by the two methods. At the end of the irrigation interval the difference

Fig. 31: Transpiration rate of individual trees at the beginning and the end of irrigation interval, irrigation was applied on Julian day 279, trees 7 and 8 were irrigated every 3 days.

Fig. 32: Transpiration rate, normalized to the rate at the first day after the irrigation, each point is an average of 6 trees.

Fig. 33: Accumulated transpiration rate of a single tree and soil water loss during an irrigation interval.

between the two methods was about 7 mm (nearly 20%). The accumulated transpiration rate for 12 days during the irrigation interval in Fig. 33 was 32 mm or an average of 2.7 mm d^{-1} . The measured water loss from the soil was 25 mm on an average of 2.1 mm d^{-1} . In other trees and during other irrigation intervals the differences between the two methods were much larger. It has earlier been shown that high proportion of root system was concentrated in the upper soil layers particularly in the 0-0.3 m, therefore it may be assumed that this layer provided a high proportion of total amount of water. However, the calibration of neutron probes for measurements of soil water content is exposed to sources of error, particularly in this depth, which might be responsible for the underestimation of water loss leading to discrepancies between the two methods.

A typical response of xylem water potential at noon hours during an irrigation interval in June 1988 is shown in Figs. 34-35. The comparison is made between a reference tree which was irrigated every 3 days and two trees irrigated at 14-day intervals. Xylem water potential dropped during the irrigation interval in both, fully exposed leaves (Fig. 34) and covered leaves (Fig. 35). In the exposed leaves the total drop was about 0.3 MPa, but the variations between the days were more than $\pm 0.1 \text{ MPa}$. In the covered leaves the drop during the interval was also 0.3 MPa with daily variations much smaller than in the exposed leaves. High daily variations, particularly in the exposed leaves almost obscures the drop in xylem water potential during the irrigation interval. Although climatic variations between days may be an important factor for the variations in xylem water potential, the data given in the two figures suggest that xylem water

Fig. 34: Drop in xylem water potential in exposed leaves during irrigation interval.

Fig. 35: Drop in xylem water potential in covered leaves during irrigation interval.

potential is a parameter which is not as sensitive as sap flow measurement for tree response to soil water availability.

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LIST OF PUBLICATIONS

Cohen, Y., Fuchs, M., Moreshet, S. (1988) Using heat pulse to determine the effect of climate on orchard transpiration. Agronomy Abs., 1988 Annual Meetings. Anaheim, California.

Cohen, Y., Fuchs, M., Moreshet, S. (1989) Estimating citrus orchard canopy resistance from measurement of actual and potential transpiration. International Workshop on Analysis of Water Transport in Plants. Firenze, Italy.

Cohen, Y. (1990) Determination of orchard water requirement by a combined trunk sap flow and meteorological approach. Submitted to Irrigation Science.

DESCRIPTION OF COOPERATION - The principal investigator (Y. Cohen) visited the U.S. on two occasions for the purposes of a critique of the U.S. research project and discussion and arrangements for Israeli-manufactured sensors and data acquisition equipment for use in the US experiments. During March of 1989, Mr. R. Mead of the USDA-ARS Water Management Research Laboratory travelled to Israel for a three-week training period in the construction, calibration, and use of the heat pulse probes, use of associated data acquisition equipment, and computer software to be used in analyzing the raw data from the heat pulse measurements. The U.S. and Israeli cooperators have been in communication frequently during the project to determine appropriate design characteristics and operational procedures for heat pulse sensors, and to compare ideas on interpretation of data.

MAIN ACHIEVEMENTS OF THE RESEARCH

Considerable technical achievement of the study was the operation of an automated heat pulse system in the field continuously during two irrigation seasons. The ability of measuring eight trees simultaneously and sampling 3 different groups of eight trees, allowed an acceptable accuracy in extrapolation of single tree to orchard transpiration.

Since orchard transpiration was continuously monitored, it was used as criterion for irrigation scheduling. The use of this factor as criterion resulted in a better timing of irrigation and reduced seasonal water application by sixteen percent. The combinations of measurements of climatic factors for computation of potential transpiration and actual transpiration allows a significant improvement in understanding of orchard water relationship and extrapolation of the findings in this study to other orchards in different climatic conditions.

Operational problems dominated the field evaluations of both the heat balance and heat pulse work done in the US. The focus of the work in final year of the study in the US was directed more toward assessing the accuracy of these methods in determining perennial crop transpiration rates rather than using the sensors as an "indicator" of plant water status. Use of the sensors as "relative" indicators of plant water status was not addressed. Both heat pulse and heat balance approaches have been used successfully by other researchers. Differences in size of trees and species-related differences in anatomy apparently necessitate different solutions to operational and sampling problems.