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Improving Irrigation and Radiation Efficiency of Citrus Orchards by Partial Irrigation and by Canopy and Root Size Control

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IMPROVING IRRIGATION AND RADIATION EFFICIENCY OF CITRUS
ORCHARDS BY PARTIAL IRRIGATION AND BY CANOPY AND ROOT
SIZE CONTROL

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ABSTRACT

The objectives of this study were to examine the hypothesis that winter rains which wet the summer dried roots of a partially irrigated citrus orchard, cause water stress and affects growth and yield, to identify the cause of the water stress and to determine the effect of the reduction of this wetted volume on water uptake and on water stress. Experiments in outdoor environmental chambers indicated that soil water availability was the primary determinant of Carbon Exchange Rate (CER) in citrus tree seedlings. Split-root experiments with citrus tree seedlings grown in 4-compartment containers showed that CER positively correlated with the number of wetted compartments. Biomass accumulation and water use efficiency were reduced with the reduction of rooting volume irrigation. Partial rooting volume irrigation of citrus tree seedlings grown in containers with soils of low water holding capacity reduced growth due to low hydraulic conductances of the soil-root-shoot system. On the other hand, drying or pruning 50% of the roots in mature trees grown at high soil water potentials did not affect the hydraulic conductances and the average production even when the dried roots were rewetted during the winter. The preferred high soil water potential was -15 kPa at the top 0.3 m where most of the roots were concentrated. Higher flower production in the trees with the 50% dried roots indicate that stresses were involved. About 25% water was saved in the partially irrigated treatments.

OBJECTIVES OF THE RESEARCH PROJECT

Check whether reducing the wetted soil area which implies smaller water doses applied at higher frequency is causing water stress in Citrus orchards.

Check the role of the root system developing in the non irrigated soil during the rain season on the water balance of the trees.

Adjust the size of the canopy and to water uptake activity of the root system, in a partially wetted soil.

Determine the effect of reducing the wetted root volume on citrus treeing responses of photosynthesis, transpiration, growth parameters and water stress parameters.

Field Experiments in Israel

ABSTRACT

Past experiments have shown that water stress developed in citrus trees with partially irrigated area where water reached the full rooting depth. It was hypothesized that seasonal cycling of wetted root zone by winter rainfall and summer drought, causes water stress and reduces yield. Preventing winter rewetting of these roots could remedy the stress. The objectives were to identify the causes of stress, and to determine the effect of the reduction of the wetted rooting volume on water uptake and on water stress. Four irrigation treatments were applied: T 1. Full area wetted in winter as well as in summer. T 2. Partial area dried out only during summer. T 3. Partial area continuously dried out. T 4. As in 3 plus periodic canopy pruning to diminish the transpiring area and compensate for the reduction in active root length. Most roots concentrated in the top 0.3 layer. Root length density increased only in the wetted volume of T 4. Soil water potential of the irrigated soil volume was not allowed to decrease below -30 kPa. Most of the fluctuations occurred in the top 0.3 m. They were the slowest in T 1. Amount of water which was applied to T 2, T 3 and T 4 was lower by 20 to 27% than to T 1. Plant stresses as indicated by a drop in transpiration and leaf water potential, occurred when soil water potential dropped below -15 kPa. Root pruning of T 4 after a two years' continuous drying of the nonirrigated soil surface, did not change the hydraulic conductance of the tree and reduced very little transpiration. Pruning roots of T 1 did not affect conductance but reduced transpiration by 20 to 30%. Flower production of T 2, T 3 and T 4 was enhanced compared to the flowering of T 1. Average yield of all treatments was similar. In "on" years of the alternate

fruiting cycle T 1 produced a 15% higher yield. Canopy pruning did not increase the average yield nor did it change the balance yield in the tree profile.

INTRODUCTION

Israel has more than 35,000 hectares of mature citrus orchards growing in a Mediterranean climate with a rainy winter and a dry summer. In Florida, there are over 325,000 hectares of citrus with average annual rainfall exceeding evapotranspiration, but rainfall deficits typically occur in the spring months, with drought usually being severe during April and May (Allen et al. 1982, and Butson and Prine 1968). In Florida, citrus orchards are found in two widely different site conditions: on deep, well-drained soils of the Central Florida Ridge Land Resource area, and on shallow, high-water-table soils of the South Florida Flatwoods Land Resource area which is poorly drained. Irrigation by overhead sprinkler has been the common practice in upland areas, whereas crown-flood irrigation is common in high-water-table areas (Calvert et al. 1967). Root-zone moisture is particularly critical in the high-water-table soils because feeder roots are usually limited to 40-45 cm (Allen et al., 1978, unpublished, Calvert et al. 1977) and the soils are sandy with low water-holding capacity. The common irrigation practice is to wet the entire soil area of mature orchards to full root zone depth. By contrast, minisprinklers and drippers are wetting only part of the soil area near the trunk or along the tree rows. The current trend is to replace complete by partial wetting of the orchard soil area. The new irrigation methods have not yet been proven to be beneficial. In many of the experiments comparing new versus traditional systems, the same amount of water was applied to both, resulting in deeper penetration of water in smaller wetted area. In a previous experiment (Moreshet et al., 1983; Cohen et al., 1987) a partially wetted area and a fully wetted area were irrigated to equal root zone depth. The partially wetted treatment was irrigated more frequently in order to keep the same range of

soil water potential variation in both treatments. Nevertheless water stress developed in the trees of the partially wetted area, both water uptake and leaf water potentials were lower, and yield was reduced.

During the winter, rain wets the entire area of the soil. If soil temperature is not limiting (Monselise, 1945; Kozlowski, 1971; Castle, 1978) new roots develop in the nonirrigated soil. This fraction of the soil will gradually dry out, at a rate depending on surface evaporation rate, new root activity and available moisture content. Results of the previous experiment showed (Moreshet et al., 1983) that water potential of the unwetted soil dropped and reached wilting water potentials in parts of the profile. The gradual depletion of water from a compartmented dry soil by roots which extend to wet soil has been reported (Herkelrath et al., 1977). The roots of the drying part of the soil are going through a degradation process and finally stop their activity (Kriedemann and Barrs, 1981). Despite this degradation, the rain restored the rate of water uptake of the partially irrigated trees to its initial value at the end of the winter (Moreshet et al., 1983).

It is reasonable to assume that growth, activation and gradual drying of part of the roots will cause water stress and decreased yield. Water stress is possibly avoided if roots development in the dry zone is stopped by preventing rewetting by rain. As a result more resources are available for denser root growth in the wet soil. The compensation may not be complete since the relation between water uptake and root density is not linear (Taylor and Klepper, 1978). Moreshet et al. (1987) found that reducing root density of soybean plants by as much as 50% reduced transpiration by about 80% only. Bialoglowsky showed (1936) that, beyond a threshold, water loss per unit leaf area of rooted lemon shoots was reduced as the amount of roots per unit leaf area dropped.

The high rate of water depletion from a small volume of soil could cause a rapid decrease in the soil hydraulic conductivity and impede water transport to the roots. Consequently, water uptake per tree may be less than that of trees with unconfined soil moisture volume. Reducing the leaf area may partly reestablish the imbalance. Stanhill et al. (1982) removed leaves in layers from bottom to top of a mature Valencia orange tree and reduced transpiration. Cohen et al. (1987 a&b) presented a citrus canopy model describing the effect of leaf structure and distribution on radiation absorption and predicted that pruning of the canopy diminished transpiration. The literature indicates that pruning does not reduce yield (Aluf and Tal 1980, Fucik 1982) but increases the relative fruiting of the lower canopy (Fucik, 1982).

In summary, we hypothesized that the water stress in partially irrigated trees was caused by the progressive drying of part of their root system which followed their reactivation during the previous winter. Preventing rewetting of the nonirrigated soil volume, may inactivate these roots and possibly avoid the summer stress. Pruning part of the canopy may reduce the transpirational demand and compensate for the lost roots.

MATERIALS AND METHODS

Site:

The experiment was conducted in a 'Shamouti' orange orchard (*Citrus sinensis* L. Osbeck) grafted on sweet lime (*C. limmettoides* Tan.) inarched with sour orange (*C. aurantium* L.) rootstock. It was located at Bnei Dror in the central coastal plain of Israel. The climate is Mediterranean with a dry summer and rainy winter (more than 500 mm average

rainfall). The trees were planted in 1958 at a spacing of 6x4 m in a sandy loam soil. Average maximum height of the trees in summer 1987 was 5.75 m and average of their maximum width 5.40 m.

Experimental Design:

The experiment consisted of four treatments in four replicates, each of 15 trees, 5 trees in 3 rows, three central sampling trees surrounded by 12 border trees: 1. Irrigation with sprinklers (Na'an 501), one per tree located between the trees along the row, with an output of 0.12 cubic meter of water per hour. 2. Irrigation with minisprinklers (Ein-Tal), two per tree along the row at equal distance, applying each 0.06 cubic meter of water per hour. 3. As in 2 with an additional winter mulching of the soil between the rows by polyethylene sheets, 3 m wide. 4. As in 3 with an additional pyramidal pruning of the canopy in March of 1984 and 1987. All other treatments were pruned once a year in alternate alleys. In the Spring of 1986 the roots of the trees in the previously mulched treatments were pruned to a depth of 1 m by opening a 0.1 m wide trench running parallel to the row 1.5 m away from each side of the trunk.

The replicates were organized in four blocks and treatments were randomized within each of the blocks.

Measurements:

Soil Moisture: A neutron probe was used in one tree per treatment in two out of the four blocks. The probe was separately calibrated for the layer of 0-0.3 m and for all the layers below this depth. Twelve access tubes were installed in one quarter of the area of one tree (2x3 m) in four rows, three tubes per row down to 1.5 m. Two tensiometers (0.3 and 0.9 m deep) were placed in each replicate of all treatments at a distance of 0.9 m from the

trunk row. This was the distance with the average distribution of water coming out from the minisprinklers. In one of the blocks three extra tensiometers (0.6, 1.2 and 1.5 m deep) were placed at a similar distance from the trunk row. Irrigation was applied whenever the tensiometers of 0.3 or 0.6 m reached 0.03 MPa replenishing the extracted water as computed from the neutron probes readings.

Plant Moisture: Water uptake was measured by the heat pulse method (Cohen et al., 1981). Three probes bearing six thermistors in a line and three heaters were inserted into the trunk in three orientations to obtain the distribution of sap flow. Once the relationship between orientations was obtained a single probe was used per tree. Maximum number of probes in use was six. Leaf xylem water potential was measured with a pressure chamber (Arimad 2, Kfar Haroob, Israel) on leaves in full sunlight, open shade and deeply shaded leaves covered with aluminum foil one day before the measurements (three replicates of each).

Sunlit fraction: The illuminated fraction α of the outer shell of the canopy was evaluated hourly by examining eight sections of the canopy of each measured tree. Average estimates of various observers did not vary by more than 10%.

Root Distribution: Roots were sampled from one quarter of the area occupied by each examined tree. This area was divided into four strips parallel to the tree row line and each strip into three sections. All together roots were sampled from twelve point. A cylindrical drill of 0.08 m in diameter was used to sample the top 0.3 m in three sublayers of 0.1 m. The layers below, each of 0.3 m were sampled by a cylindrical thin wall tube of 0.04 m in diameter. Roots were washed, feeder roots were separated from the thicker roots and dried. Length was measured by a calibrated Delta T Area-Length meter or by an equivalent set of HP plotter, HP computer and a projector as described in the next paragraph.

Environmental Conditions: A datalogger (Campbell CR21) collected solar radiation, air and soil (at 0.3 m beneath a tree) temperatures and relative humidity. The prevailing summer days were typically clear to partially cloudy with maximum air temperatures of 28 to 32 oC. and 40 to 60% RH.

Fruiting and Yield: Flower and fruitlets abscission was counted twice a week, every year at the same location, in a grid of 16 cardboard boxes, 0.27 x 0.38 x 0.13 m under one side of a tree in each treatment. The final numbers were computed on the basis of the relative area occupied by the boxes. Trees included in the sample were picked individually. Yield was divided in two layers with a separating line at 2 m height. Fruit weight was evaluated from a subsample of 50 to 100 fruits for each layer. Juice quality was tested on 15 fruits per subsample.

RESULTS

Root Distribution:

The reliability of the coring method for measuring root density depends, among other factors on the number of replicates. But sampling density is limited because of damage made to the root system. The roots are concentrated in top 0.3 m layer. The horizontal distribution of roots was tested in a two meter long trench 1.5 m away from the tree row line. The number of root tips was counted in a grid of rectangles of 0.08x0.1 m (equivalent to the size of the sampler auger) in three top layers of 0.1 m each. The frequency of root numbers is shown in Fig. 1. The numbers were normally distributed with the highest number of root tips in the range of 25 to 40. This clustering of the roots

emphasizes the difficulties of the sampling. In order to reduce the variation (standard deviation averaging at about 45%) resulting from the clustering we averaged the three core samples in a strip parallel to the tree line which did not show any trend in relation to the distance from the trunk. All the following root data are averages of the three core samples in the strip.

Prior to the application of the differential treatments, root length density derived from weight and a correlation between length and weight, was examined to a depth of 1.5 m. Results are shown in Fig. 2. The soil below 0.9 m had only 5% of the total root length. As the errors caused by sampling, washing and length measurement are larger than 5%, data collection was limited to 0.9 m. The horizontal distribution of root length density between two tree rows (Fig. 3) down to a depth of 0.6m is irregular. Deeper it increases with distance from the trunk line. Soil moisture depletion is another indicator of root distribution. Fig. 4 shows the depletion at four distances from a tree trunk line during a prolonged drying period. At the depth of 0 to 0.3 m the rate of depletion was similar at all four distances. At the depth of 0.3 to 0.6 m the soil closer to the trunk dried out faster than the others. Changes in moisture at the depth of 0.6 to 0.9 m were minor except near the trunk.

Root density was measured several times during 1984 to 1986 in the treatments which were partially wetted by minisprinklers. Fig. 5 shows that partial wetting decreases root density at the depth of 0 to 0.3 m as irrigation season progresses except in T 4. No differences were found below 0.3 m.

Partial irrigation develops a strong horizontal gradient of root density in the top soil layer (Fig. 6), with a low root density in the non irrigated zones. Treatment 2 where winter rains were allowed to rewet the dry zones behaves like the treatment with plastic cover, in contradiction with the

initial hypothesis that winter rain produces a regrowth of roots in the zones of the soil where irrigation during the summer did not reach. The total root length per tree (as computed from the above data) (Fig. 7) ranged from 100 to 200 km. Apart from treatment 4 variation with time was quit large.

Soil Moisture:

The moisture depletion decreased with depth (Figs 8, 9, 10). Water extraction from the 0.6-0.9 m layer in the partially wetted treatments 2, 3, and 4 was larger than in the completely wetted treatment 1. The plastic films preventing rain rewetting of the dried zones of soil in treatments 3 and 4 did not affect the moisture extraction. The soil moisture measurements show a minor contribution of the layers below 0.90 m to the water balance of the trees (Fig. 11). The drying rate of treatments 2, 3 and 4 was higher than in treatment 1 with the fully wet soil. This effect is accentuated in the top layer.

The consistency of the threshold moisture prior to irrigation during the three seasons is shown in Figs 12 to 14 for the three top layers. Variation within and between years in each of the treatments was minor. Variation in post-irrigation moisture content was larger. The pre-irrigation moisture content in the top layer (Fig. 12) and in the second layer (Fig. 13) of treatment 1 was higher than that of the other treatments. The values of T 1 are averages which were obtained from all data while those of the other treatments are averages from the wetted area which obtained a decreasing amount of water with the distance from the emitters. Hence the average moisture of the latter treatments is lower than that of treatment 1.

Soil Water Potential:

Tensiometric soil water potential measurements triggered

irrigation. The chosen threshold potential was -30 kPa at the depth of the main root zone (0.3 m). Irrigation was occasionally started when the threshold potential of -30 kPa was reached first at the depth of 0.9m. The following Figures (Fig. 15 and Fig. 16) show the three seasonal trends in potential between irrigations in the four treatments at the depths of 0.3 m and 0.9 m. The rate of potential decrease is slow when the soil is wet and accelerates at about -10 kPa. The rate of change in treatment 1 (sprinkler-irrigated) was slower than the rate of potential change in the other treatments. Apart from treatment 4 the values were quite high. The average potentials at the depth of 0.9 m reached -15 to -20 kPa before irrigation was applied because less water was extracted from this layer. Below 0.9 m changes were minor.

Irrigation:

The water requirement was computed from the measured depletion of moisture below field capacity in the irrigated soil profile. Water application per day is presented in Fig. 17. The numbers 1 to 4 stand for treatments 1 (sprinkler irrigated) to 4 (minisprinklers with canopy pruned and soil covered, or trimmed roots). Applied water in treatment 1 was 4 to 5 mm per day in the mid summer and about 3.5 to 4.5 mm per day in the treatments which were irrigated by minisprinklers. Soil moisture was occasionally measured after irrigation. Hence water loss could be calculated from 1 to 2 days after irrigation until the day of the following irrigation (Fig. 18). It can be seen that for these days the detected water loss was only 2 to 3 mm per day in treatments 2 to 4 and about 3 to 3.5 mm in treatment 1. These values are similar to the water uptake measured by the heat pulse method.

As irrigation was initiated at the same preset soil water potential in all treatments the irrigation frequency was smaller in treatment 1 than in the other three. This was

expected because of the larger wetted soil volume with active roots of the sprinkler-irrigated treatment 1. Differences between the three partially wetted treatments were small and not consistent with time (Table 1). The water requirement (cumulative) of all four treatments in 1985, 1986 and 1987 is shown in Fig. 19. The total amount of water that the treatments with the limited root volume received was smaller than the amount which the sprinkler-irrigated treatment received by 20% to 30%. The small difference within these treatments was not significant apart from treatment 3 which required 5% less water than the others (Table 1).

Table 1: Three Season's Water Requirement of Four Irrigation Treatments. Shamouti Orange Orchard, Bnei Dror.

Year:	1985	1986	1987	Average
Treatment:	m ³ /1000 m ²			
**	*	*	*	*
1	(13) 847	(11) 743	(10) 734	(11) 775
2	(18) 675	(17) 566	(19) 585	(18) 609
3	(21) 622	(16) 553	(16) 529	(18) 568
4	(21) 680	(15) 556	(16) 591	(17) 609
	% of Treatment 1			
1	100	100	100	100
2	80	76	80	78
3	73	74	72	73
4	78	81	75	80

* Number of irrigations per season.

** 1 - Sprinklers. 2 - Minisprinklers control.

3 - As in 2 + soil cover. 4 - As in 3 + root pruning.

Water Uptake and Leaf Water Potential:

a: Short term effects of root pruning.

The immediate effect of severing part of the roots of trees in treatments T 3 and T 4, where a plastic mulch had prevented rewetting by rain, was compared to the immediate effect of root cutting in trees with a fully wetted soil.

Since we did not want to disturb the trees from treatment T 1, trees from a sprinkler irrigated border row outside the experimental blocks were selected (T 1'). Trees from T 1' were divided into two groups of three, T 1'A and T 1'B. Roots were pruned in T 1'A. The pruning procedure was similar to that which is described for T 3 and T 4 in the chapter METHODS - Experimental Design. T 1'B served as a control. Roots were pruned in three trees from T 4 which were previously covered during winter by a plastic mulch. Three trees from T 2 served as their control. The pruning of the roots is expected to provide information on the relative contribution of the removed root portion to the water uptake by the trees in both treatments. It may also enable testing the hypothesis that the existence of roots in the drying soil portion has an adverse effect on tree water status.

Root density in T 1' is comparable to the density observed prior to the beginning of the experiment (Fig. 3). Pruning the roots at a distance of 1.5 m from the trunk row reduced their size by 40 to 50%. The percent reduction in T 4 was much smaller as is learned from Fig. 6 which compares root length density in the vicinity of the tree trunk row (Fig. 6A) to the density between the rows (Fig. 6B). Transpiration and leaf xylem water potential were measured twice in each of the 12 trees; once prior to the pruning of the roots and once after pruning the roots of six of them. Measurements were always taken one day after irrigation.

Diurnal curves of transpiration rate before and after root cutting in trees from T 1' are shown in Fig. 20. Water uptake by trees from T 1' dropped by 20 to 30% after root cutting (see also Table 2). The control trees showed no significant differences in water uptake on the same two days indicating that all environmental conditions which may affect transpiration rate were similar in both days including soil water potential. Transpiration rate from T 4 trees had no consistent response to root cutting. In one of the two trees there was no effect of root cutting on transpiration rate

(Fig. 21) but in the other tree transpiration rate after the cutting was slightly lower than before the cutting. However similar differences were also observed in the control tree from T 2. These trends are also shown in the total daily transpiration (Table 2). It means that the environmental differences rather than root cutting caused the reduction in transpiration in trees from T 4.

Table 2: The effect of root cutting on daily total transpiration rate (accumulated from hourly rates) of trees irrigated by sprinklers (T 1') or minisprinklers (T 4 and T 2). 1986.

Tree No	Sprinklers T 1'				Minisprinklers T 4 T 2			
	18.6	16.7	18.6	16.7	24.6	1.7	24.6	1.7
	-----	-----	-----	-----	-----	-----	-----	-----
	Before Pruning	After Pruning	Control		Before Pruning	After Pruning	Control	
1	108	85	105	101	113	114	135	138
2	68	54	---	---	100	91	132	114
3	121	82	102	108				

Diurnal curves of sunlit and shaded leaf water potentials in T 1' trees are shown in Figures 22 and 23 respectively. Before root pruning measurements were taken in the first half of the day. After pruning measurements were taken in the afternoon, therefore comparison is difficult. Yet, a drop in leaf water potential of 0.2 to 0.4 MPa in both , sunlit and shaded leaves following root cutting can be observed. No such differences can be seen when comparing the two days in the control trees. Fig. 24 and 25 show the response of leaf water potential to root cutting in trees from T 4 as compared to leaf water potential of control trees from T 2. In sunlit (Fig. 24) and shade leaves (Fig. 25) water potentials were similar in all trees on both days suggesting that root cutting had no effect on leaf water potential.

The data presented so far indicate that the contribution of the root system between the rows to tree water uptake is significant providing this part of the soil is irrigated during the summer season. The immediate response of removing this root portion was a drop in transpiration rate and a decrease in water potential of the tree. But when the root volume between the rows is not irrigated during the summer, its activity is small. Therefore, the removal of this part of the root system did not have a significant effect on the transpiration rate and on leaf water potential. Since T 4 did not react differently than T 2 after cutting the drying roots it does not support the hypothesis that the drying-wetting cycle of the soil induced water stress. Fig. 26 shows the relationship between sunlit and shade leaf water potential and transpiration in one treated and one control tree from T 1'. The slope of this relationship is an expression of the total hydraulic resistance of that tree. Although the number of data points is small and although leaf sampling before and after root cutting was made on different parts of the day the curves suggest no effect of root cutting on the slope of the relationship. However the intercept of the regression line was lower following root cutting while no such difference was observed in the control trees. Yet we were not able to quantify the relative contribution of the cut roots to the total root resistance. Such a quantification is proposed in one of the following paragraphs (The Driving Force of Sap and the Hydraulic Conductance). A resistance analysis in one tree from T 2 (Fig. 26) shows that the relationship between leaf water potential and transpiration did not change after cutting the roots. It means that the contribution of the cut roots to the hydraulic resistance of this tree was small at that period of the year when most of the roots in the summer-dried soil were inactive.

b: Long term effects of root pruning.

The average interval between irrigations was about 10 to 12 days in treatments 2 to 4 and about 18 to 20 days in treatment 1. In mid summer the intervals shortened to 8-10 days and 13-15 days respectively. Soil water potential dropped occasionally below the threshold of 30 kPa since the rate of change in potential below 30 kPa was sharp and hence stressed the trees. This stress was examined by relating measured water uptake to leaf water potential.

On two occasions water uptake was followed between two irrigations. Fig. 27 shows the diurnal trends in water uptake during the first cycle (10 to 23 of August 1988) in three of the treatments, 1, 2 and 4. Treatments 1 and 4 were irrigated on the 12th of August 1987. Treatment 2 was irrigated on the 9th and again on the 17th. Uptake measurements in treatment 2 started four days after its first irrigation. Uptake rate decreased from the first day of measurements (4th day after irrigation). The total water uptake per day (Fig. 28) demonstrates this drop. The drop started two days after the second irrigation. Water uptake in treatments 1 and 4 returned to the starting values one day after irrigation was applied and dropped from then on. The other cycle was longer and the soil water potential dropped below the threshold of 30 kPa in treatments 2 and 4. Fig. 29 shows the diurnal course of sap flow in the three treatments during the drying cycle and three days after the following irrigation (25th of August to 10th of September). In the two treatments with the limited soil volume, uptake slowed down considerably (2 and 4) four to five days after irrigation. In treatment 1 (full wetted soil volume) water uptake decreased less and later. The observed evolution of uptake is reflected in the measured soil moisture depletion which started fast in the top three soil layers of treatment 4 (down to 0.9) and lessened later (Fig. 30). The tensiometric soil water potential decreases (Fig. 31 C) faster below -20 kPa in treatments 2 and 4. The decrease of soil water potential in treatment 1 is slow and does not drop below -20 kPa. The corresponding water uptake rate remains nearly

constant through the irrigation cycle Fig. 31 A&B). By contrast the accelerated decrease of soil water potential in treatments 2 and 4 are paralleled with a lowering of the water uptake rate.

Leaf water potential (LWP) of sunlit, skylit (outer crown section facing away from the sun) and leaves in continuous shade covered with aluminum foil (see Methods) was measured at midday in the same trees on the same days as above. In general leaf water potential in treatments 2 (T2) and 4 (T4) was lower than in treatment 1 (T1) (Fig. 32). The effect of the drying of the soil on sunlit LWP was not clear. Shaded LWP of T 2 and T 4 was significantly lower than that of T 1 immediately after irrigation. It decreased during the drying cycle in all treatments. The steepest drop occurred in T 4. The LWP of covered leaves differentiated most consistently between treatments. This LWP is higher in T 1 through the drying cycle, including the period immediately after irrigation. The steep drop in T4 corresponds to the fast tensiometric potential decrease after day 246 (Fig. 31 c).

Earlier studies (Cohen et al 1983, Moreshet et al. 1985) established a linear relationship between LWP and flow of sap. Its slope represents hydraulic resistance of the citrus tree and the zero intercept is the threshold LWP above which there is no measurable water uptake. The resistance does not change with soil moisture content. The threshold LWP decreases as the soil becomes drier.

We related midday measurements of LWP to the sap flow (Fig. 33). Each of these points is part of a line which represents the resistance of the particular day of measurement being the maximum flow and minimum LWP of the day. The lowest scatter of the points was in the non transpiring covered leaves. the highest scatter was found in the sunlit fully transpiring leaves. In shaded and covered leaves a linear regression was fitted to the data ($R^2 = 0.9$). According to the trend set by these data, uptake would stop

when the midday potential of shaded or covered leaves drops to -2.9 MPa. The linkage between decrease of LWP and sap flow as the soil dried confirm the conclusions drawn by Cohen et al. (1983) that soil water depletion affects the LWP at zero sap flow but not the resistance. The points from the three treatments fell around the same line. This line is probably the lower boundary of the relationship between water potential of shaded and of non transpiring leaves to sap flow under limiting soil moisture conditions.

The Driving Force of Sap and the Hydraulic Conductance:

The hydraulic conductance of plants is a fundamental property that determines the flow of water through them. The liquid pathway of water from the soil through the roots, stems and leaves is frequently lumped in a single conductance (Reicosky and Ritchie 1976, Cohen et al. 1983, Cohen et al. 1987). The relative importance of the roots as a barrier to water transport is still under debate. According to some the conductance of roots is higher than that of the organs above the ground (Nnyamah 1978, field grown mature Douglas fir tree). Others contend that the roots' conductance is small compared to that of the aerial organs (Running 1980, lodge pole pine). Kriedemann and Barrs (1981) following Ramos and Kaufmann (1979), claimed that root hydraulic resistance is the dominant component of citrus hydraulic resistance. In this section we compute the conductances of the root system and of the canopy and develop another expression for the driving force of sap.

The sap flow (F), under steady state conditions, is :

$$(1) F = K(\psi_o - \psi_w)$$

where ψ_w is the water potential at the downstream end of the liquid pathway through the plant, which has an hydraulic conductance K, and ψ_o is the potential in the roots. The definition of the downstream potential in mature trees is

complicated. The common assumption is that only sunlit leaves are transpiring and hence ψ_w is the water potential of these leaves. Lascano (1982) assumed that other leaves in the canopy also transpire. He, Van Bavel and Ahmed (1976) measured an average potential of randomly chosen leaves in horizontal layers of annual crops as representative of the true driving force at these layers. We assume that all sunlit leaves have the same leaf water potential, ψ_{il} , and that the potential of shaded leaves is ψ_{sh} . With equal hydraulic resistance of the liquid pathway between the substomatal cells of all the leaves and the trunk, the equivalent water potential of the entire foliage is simply:

$$(2) \psi_w = \alpha \psi_{il} + (1-\alpha) \psi_{sh}$$

where α is the fraction of sunlit area. The importance of α in Eq.[2] is illustrated in Fig. 34 where the sap flow in the two branches, one to the East and the other to the West, of a bifurcated Valencia orange tree follows the variation pattern of α much closer than the diurnal course of the leaf water potential.

Covered leaf water potential, ψ_c , is the xylem water potential along the conducting system (Begg and Turner 1970, Meyer and Ritchie 1980, Bristow et al. 1984) or in the branches near the connecting point of the leaf. With steady state

$$(3) F = K_r (\psi_o - \psi_c)$$

where K_r is the hydraulic conductance of the root system, assuming that the major resistance to flow is in the roots. The conductance of the aerial organs, K_p , is obtained from Eq. (1) and (3) as

$$(4) K_p = 1 / (1/K - 1/K_r)$$

The assumption that leaves in shade transpire is tested

by the comparison between shade leaves' water potential (ψ_{sh}) and covered leaves' water potential (ψ_c). If shade leaves did not transpire then $\psi_{sh} = \psi_c$. Fig. 40 shows that $\psi_{sh} < \psi_{fc}$. Fig. 35 A describes the relationship between ψ_{sh} and ψ_c in a Valencia orange tree and Fig. 35 B in two Shamouti orange trees. The relationship deviated from the 1:1 line, $\psi_{sh} < \psi_c$ during most of the day and approaches the 1:1 line when none of the leaves was transpiring (commonly at predawn). Fig. 36 relates LWP in an east branch of a Valencia orange tree having only two main branches with similar canopies, to LWP in a west branch. A relatively small deviation in ψ_{sh} between West and East occurred mostly in the morning hours (Fig. 36 A). The ψ_c in the east branch and in the west branch were similar (Fig. 36 B) which is expected if they do not transpire. 36 C relates ψ_{il} in the west to ψ_{il} in the east. ψ_{il} was similar in both branches during most of the day. Practically transpiration rate is similar within each category of tested leaves.

Diurnal measurements of F , ψ_c and ψ_c (Fig. 37) are linearly regressed to determine the values of K , Kr and as they appear in Eqs.[1] and [3]. The value of Kp is derived from Eq[4]. The results are presented in Table 3.

Table 3: Hydraulic Conductances and Upstream Water potentials as Calculated in One Valencia and Two Shamouti Orange Trees.

Eq.:	ψ_o 1	ψ_o 3	K 1	Kr 3	Kp 4
Tree:	MPa		$10^{-6} \text{ m}^3/(\text{sMPa})$		
Valencia	-0.66	-0.64	38.3	66.7	90.1
Shamouti 1*	-0.45	-0.39	26.9	70.4	43.5
Shamouti 1**	-0.64	-0.52	31.5	106.4	44.8
Shamouti 2*	-0.44	-0.39	30.5	90.1	46.1

* Measured on 5.20.85

** Measured 8 days later.

*** Average $R^2 = 0.94$ (.89 to .98) for Eq. 1 and 0.89 (.81 to .96) for Eq. 3.

Eqs.[1] and [3] produce similar values of ψ_0 which are much more negative than the soil water potential. Passioura and Munns (1984) made similar findings and argued that a threshold value is needed for opening a valve in the roots to initiate water uptake. K_r is 70% of the value of K_p in the Valencia orange tree and by 60 to 130 % higher in the Shamouti orange tree.

Flowering, Yield and Water Use Efficiency:

Flowering: Flower and fruitlet abscission was measured from 1985 to 1987. Fig. 38. shows the cumulative numbers collected in the Spring of each of the three years. Measurements were repeated in the same trees. There was no relation between the number of abscised reproductive organs and the final yield. In year 1986 the total production of flowers was very high in all treatments. Treatments 2, 3 and 4 (T 2, T 3 and T 4) produced much more flowers than T 1. Yet the final yield was higher in T 1 (Table 4). It seems that the reduced active root volume caused some stress which activated the production of more flowers but on the other hand reduced the yield. The same tendency was observed in 1985. Among the minisprinkler irrigated treatments, T 4 produced more flowers than T 2 (control) in both years. The lower number of flowers in T 4 relative to T 3 in year 1985 could evolve from the pruning of T 4 in spring of 1984. This pruning probably caused the doubling of flower production in year 1986 relative to the other treatments. The effect of this pruning can be seen in Fig. 39 which shows the cumulative seasonal abscission relative to the distance from the trunk. In 1985, one year after pruning, T 4 produced equal number of flowers in both sides of the trunk. In the following year the numbers in the west side were higher than in the east. In the other treatments the relative density of flowers in both sides depended on their past pruning. The flowering rate in year 1987 (Fig. 38) was exceptionally low in all treatments. Yet this had no effect on yield (Table 4).

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4).

Yield: A base line yield was harvested in the winter of the year before the differential treatments were applied. Yield of the following years was related to it in order to reduce the effect of the biological variability (Tables 4 and 5).

Table 4: Total Yield of Orange Fruit in the 4 Irrigation Treatments from Year 1983/4 to Year 1987/8. Bnei Dror.

Table 4: Total Yield of Orange Fruit in the 4 Irrigation
----- Treatments from Year 1983/4 to Year 1987/8. Bnei Dror.

TRT	Ton/Hectare					
	Basic 83/4	84/5	85/6	86/7	87/8	AVG84-7
1	91.5 a*	88.6 a	35.5 a	91.9 a	62.7 a	69.7 a
2	94.2 a	79.3 a	38.8 a	82.1 a	60.4 a	65.1 a
3	90.7 a	73.5 ab	36.5 a	78.5 a	68.5 a	64.2 a
4	100.4 a	54.8 b	45.5 a	88.5 a	66.4 a	63.8 a

* Yields followed by the same letter are not significantly different.

Table 5: Yield of Orange Fruit in the 4 Irrigation
----- Treatments
from Year 1984/5 to Year 1987/8 Relative to
Year 1983/4. Bnei Dror.

TRT	Fraction Relative to 83/4					
	Basic 83/4 Kg/Tree	84/5	85/6	86/7	87/8	AVG 84-7
1	225.5 a*	0.94 a	0.39 a	1.03 a	0.70 a	0.76 a
2	232.1 a	0.84 a	0.43 a	0.86 b	0.65 a	0.70 ab
3	223.4 a	0.81 a	0.41 a	0.87 b	0.76 a	0.71 ab
4	247.3 a	0.56 b	0.46 a	0.90 b	0.67 a	0.65 b

* Data followed by the same letter are not significantly different.

The total yield in absolute values (Table 4) was not significantly affected by the treatments, apart from T 4

which had a lower yield in year 84/5 resulting from the pruning. When compared on a relative basis (Table 5) significant differences were found in year 1986/7 (T 1 higher than all others) and in the averages (T 1 higher than T 4). It seems that in "on" years, when yields of T 1 were as high as in the base line year, yields of T 2, T 3 and T 4 were significantly lower. In "off" years differences were not significant. But even in "on" years the yield loss did not exceed 15%.

The pruning of T 4 did not increase the relative yield in the lower canopy (up to 2 m above ground) as is shown in Table 6.

Table 6: Yield of Orange Fruit in the Lower Part of the ----- Canopy of the 4 Irrigation Treatments Relative to the Yield of Year 1983/4. Bnei Dror.

TRT	Basic 83/4 Kg/Tree	84/5	85/6	86/7	87/8	AVG 84-7
1	63.8	0.37	0.62	0.73 a	0.32	0.51
2	76.8	0.28	0.68	0.35 b	0.29	0.40
3	63.3	0.25	0.65	0.49 b	0.38	0.44
4	73.9	0.19	0.72	0.43 b	0.32	0.41

The low sensitivity of the yield to irrigation is demonstrated in Fig. 40. It shows the relationship between the yield (Ton/Hectare) and the applied water (computed from the change in soil moisture). There was no correlation between the two when tested on a yearly basis. It seems that there are other limiting factors than water controlling production in citrus.

GENERAL DISCUSSION

The following hypotheses were made: 1. Water stress in trees with a partially irrigated soil volume is caused by the progressive drying of part of their root system which follows

their reactivation during the previous winter. 2. Preventing winter rewetting of the non irrigated soil volume, may lead to a complete inactivation of these roots and thus avoid the summer stress. 3. Pruning part of the canopy may reduce the transpirational demand and compensate for the lost roots. These hypotheses were examined in this research. The results will be reviewed and conclusions drawn.

Root Growth: None of the available methods is sensitive enough to evaluate time and space variation in root length density of citrus trees to a degree which enables distinguishing between treatment effects. The modern methods (video camera, Upchurch and Ritchie 1984) can not be used in the top 0.2 m where most of the tree roots are concentrated (see Fig. 5). The coring method which was used here has a high variability. Yet we were able to learn that the spatial distribution and variation in citrus tree roots was high. T 4, which consisted of pruned canopy with a continuously partial dried soil, increased root length density in the irrigated soil volume during the early summer.

Soil Moisture: The observations indicated that soil moisture distribution was satisfactorily controlled. Most of the water was extracted from the top 0.3 m where most of the roots were concentrated. Extraction was slower in the sprinkler irrigated treatment with the larger wet soil volume. The differences between the minisprinkler-irrigated treatments were not significant.

Soil Water Potential and Water Application: The lower threshold potential of -30 kPa was followed quite closely at the depth of 0.3 m. The rate of change in potential following irrigation was slow until a value of about -15 kPa was reached. At potentials lower than -15 kPa changes were fast. Although tensiometers sample a small soil volume relative to the total soil volume occupied by the roots the above observations are reliable since they were similar in shape and trend to changes in leaves' water potential which

represent the total tree function. Hence, the accepted threshold of -30 kPa which is commonly used in field experiments needs a second thought if stresses are to be avoided. The rate of change in the treatments with the partial soil irrigated (T 2, T 3, T 4) were faster than the changes in the treatment with the full soil cover (T 1). Differences between T 2, T 3 and T 4 were not significant. The trend in water demand and application was similar to the response of the tensiometers'. Differences between T 2, T 3, and T 4 were not large but when averaging the three years of measurement all were different than T 1 by 20 to 27%.

Stresses: Water stresses in plants which are shown as a drop in plant leaf water potential and in transpiration are caused by a drop in soil water potential. It was found here that stresses developed when soil water potential dropped below -15 kPa. This is a much higher potential than the potential which is accepted in the literature as the threshold one (Hilgemann 1963, Kriedemann and Barrs 1981). T 1 did not tend to develop stresses due to the large water storage in the soil and hence the slow change in potentials. T 2, T 3 and T 4 reached this value faster. Below the threshold soil water potential T 2 had a slower response than T 4 following the pruning of its roots. Yet in an experiment which compared the effect of root pruning on hydraulic conductances of trees from T 1 and T 2 and T 4, T 1 responded by changing transpiration while the others were much less affected.

Reproductive organs development and Yield: These responses were an integrated result of at least a year's history of short and long term stresses. Although no preplanned water stresses were applied to the treatments, undetected short term soil water potential stresses could not be avoided. The development of reproductive organs as illustrated by the abscission of flowers and fruitlets, was affected by the treatments. T 1 had significantly less organs developed compared to all other treatments. T 4

having the center space soil volume continuously dry, produced more flowers than T 2 which had its center space soil volume dried out only during the summer time. Water stresses induced flower buds in citrus trees (Reuther 1973, Barbera et al. 1985). It was also found that root pruning in satsuma mandarin encouraged the flowering (Iwasaki et al. 1959 as cited by Barbera et al. 1985). In our case the enhanced flowering was obtained by drying part of the soil volume while the other part was continuously wet. The effect of the root pruning appeared only in the flower production in spring 1987, a year with an exceptional low flower production. Contrary to the production of flowers the fruit yield in T 1 was higher by about 15% (only in the "on" years of the alternate bearing cycle) as compared to the other treatments. The average yield was similar in all treatments. The tree pruning of T 4 in 1984 did not improve the average yield in the lower part of the canopy in the following years, but reduced yield in the same year.

CONCLUSIONS

The yield reduction in the treatments with the partial irrigated soil volume was 15% in "on" years but none on the average. The water use dropped by 20 to 27%. Preventing winter rewetting of the 50% soil volume dried during the summer did not improve the yield. The yield was controlled by the lowest threshold potential in the wetted soil rather than by cycling of the potential in the non irrigated soil. It is proposed to find the lowest permissible soil volume or root length when lifting the threshold soil water potential to -15 kPa in the typical soil for citrus growth.

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FIG. 1: FREQUENCY DISTRIBUTION OF ROOT TIPS IN THE TOP LAYERS OF THE SOIL. SHAMOUTI ORANGE TREE, BNEI DROR

FIG. 2: INITIAL ROOT LENGTH DENSITY OF A 'SHAMOUTI' ORANGE TREE, BNEI DROR. APRIL 1984

FIG. 3: INITIAL ROOT LENGTH DENSITY OF SHAMOUTI ORANGE TREES IRRIGATED BY SPRINKLERS, APRIL 1984

FIG. 4: MOISTURE DEPLETION AT FOUR DISTANCES FROM THE TRUNK LINE
BETWEEN TWO IRRIGATIONS IN TREATMENT 1. 1987

FIG. 5: AVERAGE ROOT LENGTH DENSITY AT .4 TO 1.1 m FROM THE TREE TRUNK LINE. BNEI DROR.

FIG. 6: ROOT LENGTH DENSITY AT DEPTH OF 0-.3 m

FIG. 7: SEASONAL TREND IN TOTAL ROOT LENGTH PER TREE

FIG. 8: SOIL MOISTURE BETWEEN IRRIGATIONS AT DEPTH 0 - .3 m.

FIG. 9: SOIL MOISTURE BETWEEN IRRIGATIONS AT DEPTH .3 - .6 m.

FIG. 10: SOIL MOISTURE BETWEEN IRRIGATIONS AT DEPTH .6 - .9 m.

FIG. 11: SEASONAL TREND IN SOIL MOISTURE
IN THE LOWER PROFILE, 1986

FIG. 12: SEASONAL TREND IN SOIL MOISTURE AT DEPTH OF 0-.3 m
BEFORE AND AFTER IRRIGATIONS, 1985-1987.

FIG. 13: SEASONAL TREND IN SOIL MOISTURE AT DEPTH OF .3-.6 m
BEFORE AND AFTER IRRIGATIONS, 1985-1987.

FIG. 14: SEASONAL TREND IN SOIL MOISTURE AT DEPTH OF .6-.9 m
BEFORE AND AFTER IRRIGATIONS, 1985-1987.

FIG. 15:
TENSIOMETRIC SOIL WATER POTENTIAL BETWEEN IRRIGATIONS, DEPTH .3 m

FIG. 17: AMOUNT OF WATER APPLIED
TO THE 'SHAMOUTI' ORANGE TREES, mm/day

FIG. 18: SEASONAL TREND IN EVAPOTRANSPIRATION
AS COMPUTED FROM SOIL MOISTURE DEPLETION

1, 2, 3 & 4 = TREATMENT NUMBERS

FIG. 19:
CUMULATIVE WATER APPLICATION
CITRUS ORCHARD, BNEI DROR

FIG. 20: DIURNAL TRENDS IN TRANSPIRATION IN THREE TREES WITH CUT ROOTS AND TWO CONTROL TREES IRRIGATED BY SPRINKLERS. MEASUREMENTS WERE TAKEN BEFORE ROOT PRUNING (18 JUNE) AND AFTER ROOT PRUNING (16 JULY) IN ALL TREES

FIG. 24: DIURNAL TRENDS IN TRANSPIRATION IN TREES WITH PRUNED ROOTS AND CONTROL TREES IRRIGATED BY MINISPRINKLERS. MEASUREMENTS WERE TAKEN BEFORE ROOT PRUNING (24 JUNE) AND AFTER ROOT PRUNING (1 JULY) IN ALL TREES.

FIG. 22: DIURNAL TRENDS IN SUNLIT LEAF WATER POTENTIAL IN TREES WITH PRUNED ROOTS AND IN CONTROL TREES IRRIGATED BY SPRINKLERS. DETAILS AS IN FIG. 20.

FIG. 23: DIURNAL TRENDS IN SHADED LEAF WATER POTENTIAL IN TREES WITH PRUNED ROOTS AND IN CONTROL TREES IRRIGATED BY SPRINKLERS. DETAILS AS IN FIG. 20.

TREES WITH PRUNED ROOTS

CONTROL TREES

FIG. 24: DIURNAL TRENDS IN SUNLIT LEAF WATER POTENTIAL IN TREES WITH PRUNED ROOTS AND IN CONTROL TREES IRRIGATED BY MINISPRINKLERS. DETAILS AS IN FIG. 21.

FIG. 25: DIURNAL TRENDS IN SHADED LEAF WATER POTENTIAL IN TREES WITH PRUNED ROOTS AND IN CONTROL TREES IRRIGATED BY MINISPRINKLERS. DETAILS AS IN FIG. 21.

FIG. 26: THE RELATIONSHIP BETWEEN LEAF WATER POTENTIAL AND TRANSPIRATION RATE
IN ONE TREE WITH PRUNED ROOTS AND ONE CONTROL TREE. (DETAILS AS IN FIG. 20).

FIG. 27: DIURNAL TRENDS OF SAP FLOW IN SHAMOUTI ORANGE TREES
DURING A DRYING CYCLE, AUG. 1987

FIG. 28: DAILY TOTALS OF SAP FLOW IN SHAMOUTI ORANGE TREES
DURING A DRYING CYCLE, AUG. 1987

FIG. 29: SAP FLOW IN SHAMOUTI ORANGE TREES
DURING THE SOIL DRYING CYCLE OF AUG.-SEPT 1987

FIG. 30: CHANGE IN SOIL MOISTURE DURING
A DRYING CYCLE IN AUG.-SEPT. 1987
A: 0-.3 m, B: .3-.6 m, C: .6-.9 m.

1, 2 & 4 = NUMBER OF TREATMENTS

FIG. 31: DAILY TOTAL SAP FLOW, MIDDAY SAP FLOW, AND
SOIL WATER POTENTIAL DURING A DRYING CYCLE
OF THE SOIL, AUG. 25 TO SEPT. 13 1987

FIG. 32: MIDDAY LEAF WATER POTENTIAL
DURING THE DRYING CYCLE OF
AUG. 25 TO SEPT. 13

FIG. 33: RELATIONSHIP BETWEEN SAP FLOW AND
LEAF WATER POTENTIAL AT MIDDAY
DURING A SOIL DRYING CYCLE

FIG. 34: DIURNAL TRENDS IN EAST BRANCH AND WEST BRANCH
SAP FLOW, FRACTION IN LIGHT AND SUN AND SHADE
LEAF WATER POTENTIAL IN A 'VALENCIA' ORANGE TREE.

FIG. 35: THE RELATIONSHIP BETWEEN COVERED AND SHADE LEAF WATER POTENTIAL. EACH POINT IS AN AVERAGE OF THREE MEASUREMENTS TAKEN DURING THE SAME HOUR OF THE DAY. A. A 'VALENCIA' ORANGE TREE. B. TWO 'SHAMOUTI' ORANGE TREES.

FIG. 36: THE RELATIONSHIP BETWEEN AN EAST AND A WEST BRANCH
 WATER POTENTIAL OF SHADE, COVERED AND SUNLIT LEAVES
 IN A 'VALENCIA' ORANGE TREE.

FIG. 37: THE RELATIONSHIP BETWEEN SAP FLOW AND WATER POTENTIAL OF SUN AND SHADE LEAVES (WEIGHTED AVERAGE - *) AND COVERED LEAVES (o).

A: TREE 1, 20.5.85. B: TREE 2, 20.5.85. C: TREE 1, 28.5.85.

FIG. 38: THE EFFECT OF THE APPLIED TREATMENTS ON
THE ABSCISION OF REPRODUCTIVE ORGANS.
CITRUS ORCHARD, BNEI DROR. 1985-1987

FIG. 39: SEASONAL AVERAGE ABSCISION OF REPRODUCTIVE ORGANS
AT VARIOUS DISTANCES FROM THE TREE TRUNK LINE.

EACH UNIT REPRESENTS 1 m.

FIG. 40: THE RELATIONSHIP BETWEEN FRUIT YIELD AND APPLIED WATER
IN A 'SHAMOUTI' ORANGE ORCHARD, BNEI DROR.

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I. ABSTRACT

Results of preliminary studies conducted in 1985 on two-year old Carrizo citrange (Poncirus trifoliata x Citrus sinensis) and Swingle citrumelo (P. trifoliata x C. paradisi) rootstocks grown in outdoor, controlled environment chambers indicated that midday depression of photosynthetic carbon exchange rates (CERs) occurred when available soil water (ASW) was severely depleted and was exacerbated by high atmospheric vapor pressure deficits (VPD, > 3.6 kPa). Soil water availability appeared to be the primary determinant of CERs under these conditions. In 1986 citrus treeling response to partial rooting volume irrigation (RVI) was measured on one-year old Hamlin orange on Carrizo citrange, Swingle citrumelo or sour orange (C. sinensis) rootstocks grown in 4-compartment split-root containers with 4/4, 3/4, 2/4, or 1/4 compartments irrigated at 2/3 ASW depletion. Midmorning CERs were highest for 4/4 RVI trees and lowest for 1/4 RVI trees. Midday depression of CERs was evident in all treatments even after recent irrigation. High atmospheric VPDs contributed to midday depression of CERs. Diurnal evapotranspiration (ET) remained nearly constant during the day. Biomass accumulation and season long water use efficiency (dry matter accumulated/total ET) were reduced with reduction in RVI. Partial rooting volume irrigation of citrus grown on soils of low water holding capacity will likely result in reduced growth due to the inability of the soil-plant system to supply adequate water for shoot demands.

II. BACKGROUND

The economic importance of irrigating citrus in Florida was recognized when it was shown that significant yield increases were obtained by irrigating when soil moisture levels reached 2/3 depletion during wet as well as dry years (Koo and Sites, 1955; Koo, 1963). Results of numerous studies since then support these early findings.

Although Florida's annual rainfall, 1270 to 1520 mm, is more than adequate for citrus production, several factors limit water availability for plant use and thus increase the need for irrigation. First, most rainfall occurs during the months of June through October whereas rainfall from March through May may be less than that required for citrus growth. This period of deficit precipitation coincides with critical times of new growth, bloom and fruit set in citrus. Second, because most soils in Florida have low water holding capacities, 1.67 to 6.66 cm of water per meter of soil (Myers and Harrison, 1978), soil water reserves are limited and must be replenished frequently.

The citrus growing regions of Florida are often categorized according to site topography. Two major areas of citrus planting sites exist: the Central Florida Ridge Land Resource Area and the Southern Florida Flatwoods Land Resource Area (Caldwell, 1980). Ridge sites are located in a region, about 50 miles wide, that extends from the north central part of Florida approximately 200 miles to the south. This region of rolling hills and lakes has been referred to as the 'Citrus Ridge'. Soils in this region, classified as Entisols, are deep, well drained sands that permit extensive root exploration of the soil. Citrus roots on these soils have been found at depths of 2.1 to 3.7 m (Castle and Krezdorn, 1975), and feeder roots may extend to depths of 1.54 m or

more (Tucker, 1980). Until recently, the predominate method of irrigation on these sites was permanent overhead sprinklers.

In December 1983 and again in January 1985, catastrophic freezes in the northern most portion of Florida's citrus producing region destroyed most plantings on ridge sites. Consequently, many citrus plantings were established further south. Although Florida's total citrus acreage was reduced by 24%, from 761,365 acres in 1984 to 624,492 in 1986, acreage in south Florida actually increased during this time from 342,739 to 358,389 acres (Whittaker, 1985). Many of the new citrus plantings in south Florida were established on flatwoods lands.

Flatwoods sites are not confined to a certain region but are characterized by flat lands with poor drainage. The Spodosol soils on these sites have a sandy layer with low water holding capacity underlaid by a layer with reduced permeability. Shallow water tables can exist above the layer of low permeability during periods of abundant rainfall or excessive irrigation and cause flooding of the root zone. Citrus grown on flatwoods sites must be planted on raised beds to provide an unsaturated soil volume for root growth. Root systems of trees on these sites are concentrated in the upper 0.45 m of soil (Obreza and Admire, 1985; Graser and Allen, 1987). Seepage and crown flood irrigation are the most common irrigation practices on these sites.

Traditional irrigation methods in Florida, such as overhead sprinklers, seepage or crown flood, use large volumes of water. Since drip irrigation of citrus was introduced in Florida in 1971 its use has grown rapidly (Harrison and Zazueta, 1984; Fisher, 1987). Perhaps the primary factor for the change from high to low volume irrigation practices has been the growth Florida's population and agricultural

industry. To resolve conflicting interests concerning water availability and use, the Florida legislature passed the statewide Water Resources Act in 1972 which declared all waters of the state subject to regulation. Five water management districts were formed and given authority to grant legal permits which are required for physical modifications affecting water flow, quality or storage and the consumptive use of water (Baldwin and Carriker, 1985).

Expansion of citrus acreage in south Florida is expected to continue (Fisher, 1987). As the demand of Florida's urban population for fresh water also increases it is inevitable that water allocations for irrigation purposes will be reduced (Bateman, 1987). This is especially true in those districts, primarily located in south Florida, with densely populated urban areas and intensive agricultural activity. Increasingly, water allocations for irrigation purposes will be determined on the basis of water usage of efficient, water conservative, low volume irrigation systems such as drip or microsprinkler systems.

As the need to use water more efficiently has grown so, has the sophistication of irrigation technology. An extensive array of piping, pumping equipment, emitters, filters, valves, and control systems exists. Yet, lagging behind the knowledge of designing and controlling irrigation systems is the understanding of how irrigation practices affect crop growth. Although it is well accepted that plants respond positively to irrigation when soil water resources are limited, the response of particular crops to the timing and quantity of irrigation continues to be the subject of many studies. It is undoubtedly from this aspect of irrigation that the next substantial improvements in irrigation efficiency will proceed.

Irrigation water use efficiency can be improved using low volume methods largely because a reduced amount of water is applied directly to the soil volume occupied by the plant's roots thereby reducing water lost by evaporation or percolation below the root zone. Optimum water availability is maintained within the wetted zone of soil in order to meet transpirational demands of the shoot. This characteristic of low volume systems, considered advantageous in terms of water conservation, has also stimulated much concern over possible detrimental effects on crop growth due to incomplete irrigation of the root system.

Incomplete, or partial, irrigation of the root zone, and thus root system, can occur when water applied to a limited surface area moves predominately vertically in the soil in response to gravitational forces with limited horizontal movement. The soil wetting pattern is determined by the emitter type, the rate, duration and frequency of water delivery and the soil type. Limited lateral movement of water is generally a problem in coarse grained, sandy soils. In Florida, the soil moisture content at 30 to 76 cm depths decreased to below field capacity at distances 46 to 76 cm from emitters on six different soils which ranged from well to poorly drained. The maximum diameter of the wetted area under emitters with discharge rates of 1 gallon per hour on Florida soils ranges from 0.6 to 1.5 m depending on soil texture (Koo and Tucker, 1974).

Conventional irrigation practices distribute water over a larger portion of the grove soil surface than low volume systems. Roots can thus explore a larger volume of soil so that even when soil water reserves are low, short-term delays in irrigation will not have drastic effects on plant performance. When drip or microsprinkler systems are

used root development is confined to a smaller volume of soil and plant stress will occur when the available water within the irrigated region is insufficient to meet transpirational demands of the shoot. Plant stress maybe compounded when mature trees are converted from conventional to low volume irrigation practices and a part of the root system undergoes dessication. Similarly, seasonal rainfall may stimulate root growth in nonirrigated portions of the soil which in subsequent dry seasons undergoes dessication. The question of plant response to partial rooting volume irrigation can be thought of as comprised of two parts. The first part concerns the capacity of the reduced volume of active roots to supply sufficient quantities of water to the shoot and the second part is related to the stress produced when a portion of the root system is dessicated. It is the capacity of the reduced volume of roots to supply water to the shoot which is addressed here.

Numerous studies have compared the response of fruit trees to low volume and conventional irrigation practices. Generally, when adequate water is supplied, drip irrigated trees perform as well as, or better than, trees irrigated with conventional systems (Levin et al., 1974; Middleton et al., 1974; Mitchell and Black, 1974; Myers and Harrison, 1978; Elfving, 1982). Some studies have attempted to relate the under canopy surface area or volume of rooting zone wetted by low volume irrigation practices to tree performance. In Florida, Koo (1985), compared drip, under tree spray jet and overhead sprinkler irrigation of grapefruit and found that fruit production increases over no irrigation were 8 % for drip, 20 % for spray jet and 72 % for sprinkler irrigation. These results are supported by other studies conducted on sandy soils in Florida which indicate that ground area coverage is the most important

aspect of irrigation influencing tree growth and yield. These studies recommend that irrigation systems be designed to cover as much ground as possible (Koo, 1978; Koo and Smajstrla, 1985; Smajstrla and Koo, 1985).

Results of partial root zone irrigation studies of citrus conducted in Israel have been more positive and also more variable. Bielorai (1977) showed that during the first three years after initiating irrigation treatments that wet 30, 40 or 70 % of the root zone of mature citrus trees, yields were lower than those of sprinkler irrigated trees with fully irrigated root zones. By the fourth year, yields of the partially irrigated treatments were equal to, or greater than, yields of the fully irrigated treatments. In several other studies (Bielorai et al., 1981; Bielorai, 1982), mature citrus with adequate moisture in 30 to 70 % of the root zone produced yields greater than fully irrigated trees. In a separate study, grapefruit trees with 40 % of the root zone irrigated had yields equal to, or greater than, those of fully irrigated trees during the first year after initiation of treatments but reduced yields, as compared to fully irrigated trees, during the second year (Moreshet et al., 1983).

A different approach was utilized in several studies by growing plants with roots divided into four separate containers which permitted 100, 75, 50 or 25 % of the rooting zone to be irrigated. Transpiration of apple trees with 75, 50 or 25 % of the rooting volume irrigated was 94, 88 and 74 %, respectively, that of plants with 100 % rooting volume irrigated. It was concluded that adequate water was available to plants when only 25 % of the rooting volume was irrigated (Black and West, 1974). When tomatoes were grown and irrigated in a similar manner it was concluded that withholding water from 50 % of the rooting volume did not

reduce photosynthesis, transpiration or stomatal conductance as compared to fully irrigated plants (Tan et al., 1981). When water was withheld from 50 % of the rooting volume of peach seedlings during a 5-day period, photosynthesis, transpiration and stomatal conductance were reduced 23, 24 and 15 % respectively, compared to fully irrigated plants (Tan and Buttery, 1982). In both the tomato and peach study it was concluded that plants were able to extract sufficient water from the soil when only 50 % of the rooting volume was supplied with water.

The results of these studies indicate that water placement in the soil, as determined by the location, area and depth of wetting, and the duration and frequency of water application are key factors which can be manipulated to provide adequate water availability for tree crops irrigated with low volume systems. Two other factors that affect water availability, but can not be controlled by the grower, are the water holding capacity of the soil and the atmospheric evaporative demand.

Water flux through the soil-plant-atmosphere continuum can be described by the simplified flux equation:

$$T = K \Delta H$$

where:

T = total water transpired by the plant, $\text{cm}^3 \text{ s}^{-1}$.

K = conductance of the plant system. Resistance, the reciprocal of conductance, to water movement in the plant is greatest in the roots. As such, it can be considered the controlling factor for water movement in the plant when stomata are not closed. Conductance across the surface of the root system is the combination of the capacity of the root tissue to transport water (its conductivity, g_r) and the root surface area (a_r) or

volume available for water transport:

$$[\text{cm}^3 (\text{H}_2\text{O}) \text{ cm}^{-2} (\text{root area}) \text{ s}^{-1} \text{ MPa}^{-1} \times \text{cm}^2 (\text{root area})].$$

This formulation assumes that the main resistance to water transport in the plant is between the root surface and the xylem, rather than through the xylem conduit system.

ΔH = the water potential difference which exists between the soil in the root zone and the atmosphere. In practice, separate equations must be used to describe water movement in the liquid and vapor phases.

The water potential of the soil in the root zone will be determined by the water holding capacity of the soil and the amount of the water present in the soil at a given time. The water potential of the atmosphere (more properly, the vapor pressure) is determined by temperature and water vapor density. Given unlimited water availability in the soil and negligible resistance to water flow through the plant, water flux or transpiration from the plant will be directly proportional to the water potential difference between the soil and the atmosphere.

When water is applied to only a fraction of the root system of a plant, the area, a_r , portion of the conductance term, K , is reduced. For T to remain constant the conductivity of the root system, g_r , must increase (or ΔH must increase). Several studies have already shown that when the area or volume of active roots is decreased the reduction in transpiration is not linearly related (Black and West, 1974; Tan et al., 1981; Tan and Buttery, 1982). This suggests that there is some capacity for increased conductivity of the roots to compensate for the reduced root area actively transporting water. Thus, when adequate water is available in the soil a reduction in the volume of irrigated roots may be compensated for, to some degree, by an increase in the conductivity of

the roots.

If the water holding capacity of the soil is very low it will be necessary for the plant to possess an extensive root system to supply an adequate amount of water to the shoot. When only a portion of the rooting volume is irrigated there may be an increase in root g_r to compensate for the reduction of a_r , but because of the low water holding capacity of the soil there is insufficient water available in the wetted portion of soil to meet transpirational demands. Thus, when atmospheric demand for water is increased an increase in water uptake by partially irrigated trees could occur by an increase in the hydraulic conductivity of the roots. But, if the water holding capacity of the soil is low, soil water reserves may be insufficient to supply adequate water to the shoot. Consequently, the plant undergoes water stress which results in stomatal closure.

This situation of low soil water holding capacity and high atmospheric demand for water describes the environmental conditions in Florida under which citrus is grown, at least during portions of the year. The situation is most critical on flatwoods sites where high, fluctuating water tables restrict the soil depth available for root growth. Roots of these trees often have extensive lateral distribution. It is evident that the effects of reduced surface area wetting by low volume irrigation systems will be especially critical here.

The objective of the USA participation in this BARD study was to quantify the whole-plant photosynthetic and transpiration responses of citrus to partial rooting volume irrigation, to elucidate adjustments in the hydraulic status of the plant and to determine how short-term growth is affected. A second objective, to develop a model to describe water

flow through the soil-plant-atmosphere continuum and predict the ability of partial rooting volume irrigation of citrus to supply adequate water to meet the transpirational demand is still in progress.

III. PRELIMINARY STUDIES 1985

In 1985 preliminary studies were conducted which provided basic information on the photosynthesis and transpiration responses of 2-year old unbudded citrus treelings to soil moisture status and atmospheric variables when water was available to the entire root system which had developed undisturbed in 2-L containers. Seventy-two containers of each Carrizo citrange (Poncirus trifoliata x Citrus sinensis) and Swingle citrumelo (P. trifoliata x C. paradisi) were placed separately in two sunlit, controlled environment chambers and subjected to a sequence of soil water depletion cycles and variations in temperature (29 or 37 °C) and CO₂ concentrations (330 or 880 µmol mol⁻¹).

Under nonlimiting soil moisture conditions maximum canopy photosynthetic CO₂ uptake rates ranged from 10 to 16 µmol m⁻² s⁻¹ under full sunlight and remained nearly constant throughout the middle of the day. When approximately 3/4 of the plant available soil water was depleted photosynthesis was reduced and midday depression of photosynthesis was evident (Figures 1 to 4). Transpiration rates tended to be nearly constant throughout this period. Water use efficiency was lowest on days with midday depression of photosynthesis and highest after recent irrigation when excess water had evaporated from the soil surface.

Midday depression of photosynthesis was more pronounced at high temperatures (37°C) with concomitant high vapor pressure deficits (> 3.6 kPa) than they were at moderate temperatures (29°C) and moderate VPD

(2.4 kPa) (Table 1).

This initial study indicated that depletion of available soil water was the primary reason for reduced photosynthesis when light levels were high. Photosynthesis was also reduced by high vapor pressure deficits at high temperatures but only when the available soil water was severely depleted. Thus, maintenance of adequate available soil water within the rooting zone (with a thorough proliferation of roots adequate for each shoot) was essential for high photosynthesis and maximum water use efficiency. Atmospheric moisture stress appeared to be a secondary factor in reduction of plant performance and was effective only when availability of water to the roots was not adequate to meet shoot transpiration requirements. The succeeding studies conducted in Florida were aimed at quantifying plant response when water was available to only a portion of the entire rooting volume and plants were subjected to stresses of soil water deficits and high atmospheric evaporative demand.

IV. PARTIAL IRRIGATION OF SPLIT-ROOT CITRUS TREELINGS 1986

A. MATERIALS AND METHODS

1) Preparation of Citrus Treelings With Split-Root Systems

In August 1985, one-year old citrus treelings with Hamlin scions (Citrus sinensis) budded on Swingle citrumelo (Poncirus trifoliata x C. paradisi), Carrizo citrange (P. trifoliata x C. sinensis) or sour orange (C. aurantium) rootstocks were acquired from a South Florida nursery (Hutchinson's) and transported to Gainesville. 'Hamlin' is a widely grown juice orange cultivar. Sour orange has been an important rootstock in Florida for a long time and Swingle citrumelo and Carrizo citrange are

both potentially important rootstocks with growth characteristics well suited to Florida. All plant materials were chosen because of their importance and availability in sufficient quantities at the time the trees were purchased. Roots of the treelings were pruned so that four lateral roots of approximately equal diameter remained as the primary root system. The root-pruned plants were placed in 0.15-m diameter plastic pots with the four lateral roots extending from the pots through separate holes near the bottom of the pots. The potted treelings were grown in trays [.15 (depth) x 2 (length) x 1 (width) m] with soil covering the lateral roots which extended from the pots.

The treelings were grown inside fiberglass greenhouses from August 1985 to February 1986. Trees were hand-irrigated and fertilized regularly using 20-20-20 NPK with micronutrients. Water and fertilizer application was directed towards roots growing in the trays, rather than in the pots, to encourage root growth from the four lateral roots. Plants were sprayed with insecticide when needed.

Split-root containers were constructed of galvanized steel. Overall outside dimensions were 0.60 (depth) x 0.40 (length) x 0.15 (width) m and individual compartments measured 0.50 x 0.20 x 0.075 m. Each compartment was fitted with a 0.20 x 0.50 m glass panel to permit observation of root growth. Small drainage ports were built into the outside panel of each compartment situated 0.6 cm above the container floor. All seams and glass panels were sealed with silicone caulking material and each compartment was checked for leaks. Dr. Bill Castle, Lake Alfred Citrus Research and Education Center, Florida, provided recommendations for design of the containers. However, the final design was modified to allow up to 12 split-root containers to be placed in each

closed environment chamber (See also Figures A1 and A2 in Appendix A).

Citrus treelings were transferred from the rooting-trays to the split-root containers in February 1986. Only plants with four, nearly equal root masses were used. Roots were pruned to approximately equal masses, estimated visually, if growth was slightly uneven. Each root mass was placed in a separate compartment of the containers which were then filled and hand-packed with washed builder's sand. Builder's sand was chosen as the growing medium because of its textural similarity to soils in Florida, and because it was uniform and relatively free of pests. The soil moisture release curve for builder's sand is shown in Figure 5. Plants in the split-root containers were located outside. Plants were irrigated frequently and fertilized twice weekly with a 20-20-20 NPK solution with micronutrients, divided equally between the four compartments.

In May 1986, four months after the treelings had been transferred to the split-root containers, six plants were sampled for observation of root mass in each of the separate compartments. The percentage of total root dry weight found in a given compartment varied between 22 and 33%. These preliminary measurements indicate that the technique used was satisfactory for obtaining citrus treelings with 4 well-balanced, split-root systems.

2) Experimental Design and Maintenance of Plants in SPAR Chambers

Twenty-one containerized treelings were placed in each of six computer-managed, sunlit, controlled-environment growth chambers on 14 June, 1986. These chambers, developed at the University of Florida in Gainesville to study plant responses to soil and atmospheric treatments

(Jones et al., 1984), were similar to the Soil-Plant-Atmosphere Research units (SPAR units) described by Phene et al. (1978). Three outer walls of the growth chambers were constructed of Mylar polyester film and the top of a rigid plate of cellulose acetate. This portion of the transparent top of the chamber was easily removed for access to the plants. The rigid north wall was constructed of acrylic material and contained exit and entry plenums for ductwork that housed air conditioning equipment (blowers, chilled-water cooling coils, and electrical resistance heaters). The transparent top and walls allowed 88 % of the natural solar radiation to enter. Dry-bulb and dew-point temperatures and carbon dioxide concentration were measured and controlled in the canopy zone. Real time transpiration rates were calculated from cooling-coil condensate removal rates, as measured by tipping bucket rain gauges. Real time carbon dioxide exchange rates (CER) were measured by metering CO_2 to maintain a constant concentration. For this study CERs were calculated on the basis of the area actually occupied by the plant canopy (1.52 m) which was estimated to be slightly less than the ground surface area of the chambers (2.0 m). The growth chambers have been used for several years to study season long effects of elevated CO_2 concentrations on plants (see also Figure A3 in Appendix).

Seven trees on each of the three rootstocks were randomly assigned to one of six chambers. Each chamber was assigned a single treatment: 1) Fully irrigated (4/4 RVI), 2) 3/4-rooting volume irrigated (3/4 RVI), 3) 1/2-rooting volume irrigated (2/4 RVI), 4) 1/4-rooting volume irrigated (1/4 RVI) or 5) 1/4-rooting volume irrigated with a soil surface cover of St. Augustine grass (1/4+ RVI). The sixth chamber received a flooding treatment which is not included in this report.

The environmental variables measured during this study, dry-bulb and dewpoint temperatures, carbon dioxide concentration and photosynthetic photon flux density, were collected throughout the day at 5-minute intervals. Data reported here represent the mean of twelve 5-minute intervals during one hour. Data points, which occur at each hour, are not indicated on the plots.

Initial environmental controls maintained by the system were, 30 to 33°C dry bulb temperature (DBT) with a dewpoint temperature (DPT) of 18°C, which resulted in maximum air vapor pressure deficits (VPD) of 2.1 to 3.0 kPa, and CO₂ concentration of 340 µmol mol⁻¹. During the last 5 weeks of the study, short-duration (1 to 2 weeks) variations in environmental controls were imposed to observe plant response to elevated DBT (33 to 37°C), DPT (22°C), VPD (2.3 to 3.6 kPa) and CO₂ levels (880 µmol mol⁻¹).

Twenty-one split-root containers were accommodated in 0.61 (depth) x 1.83 (E-W length) x 0.84 (N-S width) m vats situated in the lysimeter portion of each growth chamber. Irrigation was effected by filling the vats with water to a level slightly below the soil surface in the containers. Drainage ports in each compartment were either sealed or left open which permitted individual compartments to be flooded or remain dry. Initially, the entire rooting volume of each plant was well watered and remained so during the first eleven days (14 to 24 June, 1986) that plants were in the growth chambers. On June 25, 1986 partial rooting volume irrigation treatments were initiated. Irrigation was scheduled on the basis of depletion of plant available soil water (ASW). The amount of ASW per chamber was determined by metering the amount of water required to bring soil water content back to field capacity at a time

when soil water content was low and plants were visibly stressed. Depletion of ASW was monitored by recording the amount of evapotranspiration (ET) collected daily as cooling coil condensate. Irrigation was scheduled when the calculated ASW was approximately two-thirds depleted. This method of irrigation scheduling resulted in an irrigation frequency that averaged 3 times per week for plants with only 1/4 of their rooting volume wetted and once every 6-7 days for fully irrigated plants (Table 2 and Table A2 in Appendix A). This management scheme was more representative of 'periodic' low volume irrigation management rather than 'continuous' or 'high frequency' trickle irrigation.

Plants were irrigated regularly with a commercial water-soluble fertilizer and sprayed intermittently with a foliar micronutrient solution. Fertilization frequency was greater for plants with partial rooting volume wetting than for fully-irrigated plants so as to compensate for the reduced soil volume and thus soil nutrient availability. All soils were 'flushed' at approximately three-week intervals to prevent harmful salt build-up.

Plant water status throughout the course of several soil drying cycles was measured using a LiCor Model 1600 steady-state porometer to determine leaf stomatal resistance and a Scholander pressure chamber for determination of leaf xylem water potential. Midmorning and midafternoon stomatal resistances were measured on three upper, recently expanded leaves of separate plants on each rootstock (9 leaves total per treatment). Midafternoon leaf xylem potential was measured similarly.

3) Harvest Procedures

a. Measurement of root hydraulic conductivity

Sampling of trees for measurement of plant biomass and root hydraulic conductivity began on September 15. Single trees from each chamber were harvested consecutively and 3 to 4 trees were harvested per day so that at any time during the 28-day period of harvest there was an approximately equal number of trees remaining in each controlled environment growth chamber.

Trees were removed from the split-root container by washing out the soil with a gentle stream of water and carefully lifting out the roots to prevent breakage. Root masses in each compartment were marked with a colored tag to indicate an irrigated or nonirrigated compartment. The center plastic pot was then snipped off and the soil washed away. In all instances roots in the center pot appeared dehydrated and dead. Each bare-root tree was photographed and placed in a container with its root system immersed in tap water. The tree was carried into the lab and allowed to adjust to conditions of low light and room temperature for 20 minutes before measurements were initiated.

Roots in each of the 4 compartments were detached from the plant at their base. In the case of very extensive root systems a single lateral root was selected for measurement of hydraulic conductivity. The root was placed in the water-filled chamber of a Scholander pressure bomb and the cut end of the root was fitted with a piece of Tygon-tubing which was then filled with water. Root exudate was collected in a covered beaker. Placement of roots in the chambers required less than 5 minutes. Pressure within the chamber was increased at an approximate rate of 0.05 MPa s^{-1} up to 0.4 MPa. Following an initial equilibration period of 15

minutes the roots remained in the chambers at 0.4 ± 0.05 MPa for a period of one hour during which exudate was collected. Four pressure chambers were used so that hydraulic conductivity could be measured simultaneously on all 4 root masses of a single plant. Six trees from each treatment (2 of each rootstock) were used for root conductivity measurements.

Upon removal of roots from the pressure chambers the diameter of the cut end was recorded. A subsample from each root mass which consisted of approximately 1/4 to 1/3 of the total root mass was separated into nonfeeder roots (diameter ≥ 1.5 mm, by visual estimation) and feeder roots (diameter < 1.5 mm, by estimation). Separated roots were placed on moist paper towels and misted frequently to prevent drying and shrinkage of roots. These 'subsample' roots were placed through a LiCor Model 3000 leaf area meter for measurement of two-dimensional surface area. Correlation of the surface areas of small segments of wire calculated from width and length measurement to the area meter values showed a close relation between the two measurements. Roots were carefully placed on the meter belt to avoid excessive overlapping. Length of subsample roots was estimated using the line-intersect method described by Tennant (1975) with 10 x 10 mm grid squares.

Area, but not length, of the remaining portion of roots used for conductivity measurement, was determined in the manner described above by separating roots into nonfeeder and feeder categories and placing them through the area meter. Roots of the subsample, sample and any unsampled portions of the roots (i.e., in the case of very large root systems, the portion not placed in the pressure chamber) were dried separately in a drying oven at 70°C for 24 hours and then weighed.

b. Measurement of biomass

Shoots of the trees were separated into new and old leaves, new and old shoots and leaf area was measured using the area meter. Because the point of shoot extension of citrus is very distinct for recent flushes of growth it was possible to distinguish older leaves and shoots from more recent (3-month old) growth with considerable certainty. Shoots and leaves were dried in the drying oven at 70°C for 48 hours and weighed. Another 9 trees from each chamber were sampled for biomass measurements only; this included leaf area and leaf and shoot dry weights as described above. Roots were separated into feeder and nonfeeder categories and dry weights were recorded.

B. RESULTS

1) Photosynthesis, Evapotranspiration and Water Use Efficiency.

Presentation of the gas exchange data collected while the trees were in the controlled environment chambers is in two parts. The first part discusses the general, diurnal patterns of photosynthetic carbon exchange rate (CER), evapotranspiration rate (ET) and photosynthetic water-use efficiency ($WUE = CER/ET$) which were observed in all treatments throughout most of the study. The plots in this section represent data obtained when 3 of the 4 rooting compartments were irrigated (3/4 RVI treatment) on 30 July 1986 with high photosynthetically active radiation (PAR) levels and 80 % plant available soil water (ASW). It is important to note that the percent ASW indicated on plots represents levels at 0700 EST of the day but that it was possible for a considerable percent of ASW to be lost by the end of the day (1900 EST). The second part of the discussion describes treatment differences observed in these responses.

Because of the large amount of data collected and the general consistency of diurnal patterns and treatment differences throughout the study, data from 1 August 1986, when ASW levels were similar, were considered to be representative of treatment differences and are presented in this portion of the discussion. Data obtained from several additional days, with varying levels of ASW, are included in the Appendix. In all instances the data presented were gathered on days when PAR levels were high.

A diurnal pattern in CERs was distinct in all treatments throughout the study and is represented by data obtained on 30 July 1986 (Figure 6). Each one-hour mean value is plotted at the beginning of the hour, eastern standard time (EST). Maximum CERs were obtained between 0800 and 1100 EST and were on the order of 4 to 8 $\mu\text{mol m}^{-2} \text{s}^{-1}$ during the early part of study and rose to 8 to 13 $\mu\text{mol m}^{-2} \text{s}^{-1}$ by the end of the study. The increase in CERs over the season is attributed to an increase in leaf area within each chamber. The reduction in CERs in comparison to those obtained in the 1985 study is attributed to the smaller plant canopy in the chambers in 1986. Carbon dioxide exchange rates typically declined during midday and reached a minimum between 1200 and 1400 EST. On some days there was an increase in CERs between 1400 and 1700 EST. Figure 6 shows that the decline in CERs occurred when PAR levels were increasing so that minimum CERs occurred during the period of highest light levels. The same data, presented in a different manner in Figure 7, suggest that other time-dependent environmental variables were influencing citrus photosynthetic response.

Figure 8 shows that the typical diurnal change in saturation water vapor pressure deficit of the air (VPD) was similar to that of PAR. Initially, plants were grown at dry bulb temperatures (DBT) which varied

diurnally between 29 and 33°C while the dewpoint temperature (DPT) remained nearly constant at 18°C throughout the day. Under these conditions VPDs increased from a value slightly greater than 1.0 kPa in the early morning to 2.0 kPa for most treatments by 1100 EST. Variation in VPDs throughout the day was largely due to an increase in DBT which was the result of changing radiation levels during the day (Figure 8). Carbon dioxide exchange rates plotted over VPD (Figure 9) show the same type of hysteresis as that observed in the light response curve (Figure 7) and suggest a strong interactive effect of PAR and VPD on CER.

From 04 to 20 August 1986 dry bulb temperature and dewpoint temperature controls were increased to 37°C and 22°C, respectively. During this period VPDs were from 1.0 to 1.6 kPa greater at 0700 and 0.5 to 1.0 kPa greater between 1100 and 1200 than under the previous temperature controls. Although daytime temperature controls were in effect between 0600 and 2000 EST, the cooling system was unable to maintain the DBT control setpoint of 29°C during the day due to rising solar radiation levels and the increased heat load within the chambers. Under these conditions DBT increased with increase in PAR which resulted in the diurnal pattern of VPD that is evident when the DBT setpoint was 29°C. With a DBT control setpoint of 37°C temperature control was facilitated and resulted in more constant VPDs during the day (Figure 10). During the period of high DBT and elevated VPDs, maximum CERs were reduced and rather than following the previous diurnal pattern with a mid-morning peak and midday depression, CERs reached a maximum before 0800 EST and declined steadily throughout the remainder of the day (Figure 11). High VPDs thus contributed to reduced photosynthetic rates.

The typical diurnal pattern in CERs observed when the citrus tree seedlings were grown under ambient CO_2 levels ($340 \mu\text{mol mol}^{-1}$) was less distinct when the CO_2 level was increased to $880 \mu\text{mol mol}^{-1}$ (11-25 August 1986). During this period maximum mid-morning CERs were double those obtained under ambient CO_2 conditions, and ranged from 15 to $29 \mu\text{mol m}^{-2} \text{s}^{-1}$. Generally, midday depression of CERs was less severe, even when the available water content of the soil was low and VPDs were greater than 2.0 kPa during the morning. Data from 19 August 1986 are representative of diurnal patterns and ranges of CERs under high CO_2 conditions (Figure 12).

The typical diurnal pattern of evapotranspiration rates under ambient CO_2 levels and 29°C DBT, represented by data from 30 July 1986, paralleled the photosynthetically active radiation (PAR) curve. Evapotranspiration rose between 0700 and 1000 EST and thereafter remained nearly constant in the range of 4000 to $5000 \mu\text{mol (H}_2\text{O) m}^{-2} \text{s}^{-1}$ or decreased steadily during the remaining hours of the day (Figure 13). When the CO_2 concentration in the chambers was increased to $880 \mu\text{mol mol}^{-1}$ ET rates rose slightly above those which occurred at $340 \mu\text{mol mol}^{-1}$ (data not shown).

The diurnal pattern of CERs combined with that of ET rates resulted in WUE values which were greatest during the early morning hours (0800 to 1000 EST) and declined steadily during the remainder of the day or rose slightly during the last hour or two. Representative data from 30 July 1986 show that water use efficiencies were usually less than $4.0 \text{ mmol (CO}_2\text{) mol}^{-1} \text{ (H}_2\text{O)}$ (Figure 14). During the period of elevated CO_2 level (11-25 August 1986), WUE was more than twice as great as values obtained at ambient CO_2 level (Figure 15).

Because CER and ET are reported by the system per m^2 of surface area it was necessary to establish that equal leaf area existed in all chambers. Base-line CERs were established by maintaining all compartments of all plants well irrigated from 14 to 24 June 1986. Daily total ET values for this period are shown in Figure 16 and do not reveal any large or consistent differences between chambers. Therefore, nearly equal leaf area was assumed. Data for 1 August 1986 were representative of treatment differences when all treatments were at nearly equal levels of available soil water depletion and are presented in the discussion. Data for several additional days illustrate responses at varying levels of ASW and are included in the Appendix. Throughout the study, maximum mid-morning CERs were consistently highest for the 4/4 RVI treatment and typically lowest for the 1/4 RVI treatment (Figure 17). In general, even when ASW was nearly two-thirds depleted in the 4/4 RVI CERs did not drop to levels as low as those which occurred at comparably low levels of ASW in the 1/4 RVI and even immediately after irrigating, CERs in the partially irrigated treatments were not as great as those which occurred in the 4/4 RVI treatment (Figure 17, and A4, A7, A10 in Appendix A).

Differences between the partially irrigated treatments were less distinct. During the middle of the day, when CERs were typically reduced in all treatments, differences were minimal or inconsistent between the 3/4 and 2/4 and 1/4 RVI treatments. In general, when soil water was more than 30 % depleted in the 1/4 RVI treatment, CERs dropped below those of all treatments, but immediately after irrigating they approached or equalled CERs obtained by the 2/4 and 3/4 irrigated plants. Typically, CERs were very similar in the 2/4 and 3/4 RVI treatments throughout most of the season (Figure 17 and A4, A7, A10 in Appendix A). This is

attributed to the variability in the volume of roots actually occupying the each of the four compartments (22 to 33 % of the total root mass) as indicated by plants harvested before initiation of the treatments.

Dry bulb temperatures in all chambers rose sharply between 1000 and 1100 EST which resulted in a marked increase in VPD in all chambers during this time. Dry bulb temperatures in chambers with 2/4 and 1/4 RVI treatments rose 1 to 3°C above temperatures in chambers with the other treatments and resulted in VPDs which were at times nearly 1.0 kPa greater than in the other treatments (Figure 18).

Evapotranspiration rates were generally greatest for the 4/4 RVI treatment and varied inconsistently and only slightly between partially irrigated treatments (Figure 19 and A5, A8, A11 in Appendix A). Both morning and afternoon stomatal conductances were low in all treatments (Table 2). Morning values (measured between 0800 and 1200 EST) ranged from 0.11 to 0.177 cm s⁻¹ and afternoon values (measured between 1200 and 1500 EST) ranged from 0.009 to 0.077 cm s⁻¹. Total water used for each treatment during the entire 94-day period of study ranged from 544 Kg for the fully watered plants to 504 Kg for plants with 1/4 RVI. Irrigation frequency increased with reduction in root volume irrigated and was twice as great for the 1/4 RVI treatment as for the fully irrigated treatment (Table 3). Water use efficiency varied between treatments during the early morning hours and was greatest for the fully irrigated plants and least for the 1/4 RVI treatment. After 1100 to 1200 EST differences in WUE between treatments were minimal (Figure 20 and A6, A12 in Appendix). Seasonal WUE on a mass basis [g (new shoot biomass) Kg⁻¹ (ET)] was greatest for fully irrigated plants and was reduced by reduction of the rooting volume irrigated (Table 3).

The St. Augustine grass cover in the 1/4+ RVI treatment occupied a surface area of approximately 1.5 m and contributed significantly to the CERs obtained in this treatment. The combined maximum midmorning photosynthetic rates of the 1/4 RVI citrus seedlings with St. Augustine grass cover were often three times higher than those obtained from the 1/4 RVI treatment without grass cover. Data presented in Figure 21 were obtained on 28 June 1986, three days after initiation of the partial irrigation treatments. Similar data were obtained later in the study (Figure 24) until the grass cover began dying in some of the unirrigated compartments. Total water use for the 1/4 RVI with grass cover was greater than for any partially irrigated treatment and 75 Kg greater than the fully irrigated treatment. When plants were sampled at the end of the study the irrigated compartment of the 1/4+ grass treatment contained a dense mat of St. Augustine grass roots. This mass of roots may have contributed to water retention in the very porous soil but also represented competition with citrus roots for the available soil water. Although seasonal water use was over 100 Kg greater in the 1/4 RVI with grass than in the same treatment without grass, both mean new citrus leaf area per plant and total new citrus tissue dry matter were lower in the 1/4 RVI+ treatment than in the 1/4 RVI without grass treatment. Consequently, total seasonal water use efficiency on a mass basis [g (new shoot biomass) Kg^{-1} (ET)] was 1.0 for the 1/4 treatment without grass cover and 0.72 for the 1/4 RVI treatment with grass cover (Figure 23, 26 and Table 1.)

2) Biomass

Leaf area index per chamber, calculated from plants sampled at the

end of the study, are reported in Table 4. Two of the plants from the 1/4 RVI treatment and one from the 2/4 RVI treatment were found to have leaky compartments, indicating that these plants actually received a greater quantity of water than the rest of the trees in their treatment. When these trees were removed from calculations and replaced with an average obtained from the remainder of the trees in the chamber, LAIs were slightly reduced as indicated by the corrected LAI values. Trees in the 2/4 RVI treatment experienced water stress and higher temperatures during the last 2 weeks of the study than in other treatments which resulted in severe leaf drop.

Simple linear regression was used to analyze the relationship of new leaf area and new biomass accumulation per plant to percent rooting volume irrigated. Plants which had leaky compartments were eliminated from these determinations. A significant linear relationship existed between the leaf area and dry wt of new leaves per plant, the dry wt of new stems per plant, the total new shoot mass per plant and the percent rooting volume irrigated (Table 4).

In general, the area of leaves as well as dry weights of new leaves and new stems were greater for plants on either Carrizo citrange or Swingle citrumelo than for those on Sour orange (Figures 27, 28, 29 and 30). Leaf area and dry weight differences between plants on different rootstock cultivars were minimal in the 2/4 RVI due to leaf drop from all plants which occurred several weeks before harvest. Biomass accumulation was reduced less for plants on Swingle than for those on Carrizo. The reduction in growth of new tissue for plants on Sour orange rootstock was not consistent with reduction in rooting volume irrigated. The implication that plants on Swingle citrumelo rootstocks may perform

better under partial rooting volume irrigation merits further investigation. Root dry weight (old + new roots) was generally greatest for Swingle citrumelo followed by Carrizo citrange and then Sour orange (Figure 31). Because these data represent root growth both before and after initiation of partial rooting volume treatments it is not certain whether roots of Swingle citrumelo grew better than those of either Carrizo citrange or Sour orange. Again, further investigation of differential response of rootstock cultivars to partial irrigation is needed.

3) Root Hydraulic Conductivity

Mean root hydraulic conductivities were calculated on a root length basis and are reported in Table 5 as $\text{mg root exudate m}^{-1} \text{ root length s}^{-1} \text{ MPa}^{-1}$. Simple linear regression analysis of the relation between hydraulic conductivity of roots to the fraction of total rooting volume irrigated was performed separately for irrigated and nonirrigated roots but revealed no significant linear trend in either case. Mean conductivities of the irrigated roots ranged from 145.9 to 299.9 $\text{mg m}^{-1} \text{ s}^{-1} \text{ MPa}^{-1}$ and for nonirrigated roots values ranged from 55.4 to 141.0 $\text{mg m}^{-1} \text{ s}^{-1} \text{ MPa}^{-1}$. These data indicate that there was no difference in the conductivities of irrigated roots among RVI treatments, and likewise, conductivities of nonirrigated roots did not vary among RVI treatments. In all treatments hydraulic conductivity of the nonirrigated roots was less than that of irrigated ones. This indicates that there was no difference between treatments in the capacity of irrigated roots to transport water and the lack of soil water reduced the capacity of nonirrigated roots to transport water, regardless of the volume of roots

per plant receiving water.

C. DISCUSSION

Information was obtained on fundamental responses of citrus tree seedlings grown under a range of irrigated root volumes and subjected to soil and atmospheric moisture stress. Gas exchange data from partially irrigated citrus plants grown on a soil with low water holding capacity show that any reduction in the irrigated rooting volume resulted in a reduction in plant performance. Fully irrigated plants had higher photosynthetic rates than partially irrigated plants. Differences between the 3/4 and 2/4 RVI plants were inconsistent or minimal. Photosynthetic rates were lowest for the 1/4 RVI plants, but did approach those of the 3/4 and 1/4 RVI trees when recently irrigated.

Several unexpected factors were involved in these responses. First, it is likely that due to the extremely low water holding capacity of the soil, water drainage was rapid and movement by capillary forces was minimal. This probably resulted in uneven water distribution in the containers such that although the ASW was not depleted it was not easily available to roots and plants were water-stressed by late morning when evaporative demand was greatest. This is evidenced by the decline in CERs in all treatments by 1100 EST, except during the period of elevated CO₂ level. Because of this, differences in CERs and ET between the partially irrigated treatments were small.

Secondly, trees with only one quarter of their root system irrigated (1/4 RVI) experienced soil water stress more frequently and more severely than the other treatments. Because of the low water holding capacity of soil it was possible for this treatment to lose as much as a third of the

ASW during one day and fall below the critical soil water level before being irrigated.

Evapotranspiration rates, total ET and total new shoot biomass accumulated during the study were greatest for fully irrigated plants and were closely related to the portion of rooting volume irrigated. Consequently, seasonal WUE was greatest for fully irrigated trees and was reduced by 8, 37, 43 and 59 %, in the 3/4, 2/4, 1/4 and 1/4+ RVI treatments, respectively. It appears that any advantage derived from partial irrigation in terms of a reduction in water usage was outweighed by the detrimental effects on plant growth due to water stress.

Water use of partially irrigated citrus with a St. Augustine grass cover (1/4+ RVI) was greater than that of fully irrigated trees but showed decreased growth with respect to the 1/4 RVI treatment. Also, seasonal WUE was lowest for the citrus grown with a grass cover. This suggests that considerable competition between the grass cover and citrus may exist when the cover crop is grown on areas where citrus root density is great.

Water transport per unit length of root did not differ between fully or partially irrigated plants, as shown by hydraulic conductivity measurements. The reduction in plant growth which occurred with reduction in the irrigated rooting volume is likely due to the inability of the irrigated root volume to supply an adequate amount of water to the plant. The necessary compensatory increase in water uptake in partially irrigated trees will likely occur as in root growth in the irrigated region of the soil.

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Table 1. Air Temperature Effects on Citrus WUE and photosynthetic quantum yield (QY) Averaged From 1000 to 1500 EST, $\text{CO}_2 = 330 \mu\text{mol/mol}$, Dewpoint = 22°C

Date (1985)	Temp (C)	VPD (kPa)	PAR ^{1/}	CER ^{2/}	TR ^{3/}	WUE ^{4/}	QY ^{5/}
25 May	31°	1.85	1470	20	11	1.8	14
23 May	37°	3.64	1300	14	16	0.9	11
24 May	44°	6.46	1280	9	20	0.45	7

^{1/} $\mu\text{mol (quanta) m}^{-2} \text{ s}^{-1}$

^{2/} $\mu\text{mol (CO}_2\text{) m}^{-2} \text{ s}^{-1}$

^{3/} $\text{mmol (water) m}^{-2} \text{ s}^{-1}$

^{4/} $\mu\text{mol (CO}_2\text{) per mmol (water)}$

^{5/} $\mu\text{mol (CO}_2\text{) per mmol (quanta)}$

Table 2. Stomatal conductance of partially irrigated citrus treeelings.

DATE	TIME	-----cm s ⁻¹ -----				
		1/4 + RVI	1/4 RVI	2/4 RVI	3/4 RVI	4/4 RVI
07 Jul 86	1300-1500	0.077	0.057	0.052	0.051	0.052
15 Jul 86	0800-1000	---	0.131	0.117	0.109	0.177
21 Jul 86	1300-1500	---	0.011	0.014	0.012	0.009
23 Jul 86	1300-1400	0.025	0.033	0.016	0.012	0.022
25 Jul 86	1000-1200	0.014	0.013	0.012	0.011	0.011
29 Jul 86	0900-1100	---	0.028	0.033	0.092	0.064
30 Jul 86	1300-1435	0.017	0.010	0.035	0.014	0.025
31 Jul 86	0900-1100	0.016	0.079	0.061	0.060	0.060
06 Aug 86	1230-1430	0.041	0.019	0.052	0.038	0.042
11 Aug 86	1100-1310	0.024	0.023	0.078	0.043	0.020
18 Aug 86	1035-1200	0.035	0.042	0.037	0.037	0.055

Table 3. Cumulative ET and Irrigation Frequency of Citrus during 94 days from June 14 to September 15, 1986.

RVI	Total ET Kg	Total ET mm	Mean ET mm/day	Irrigations #	Seasonal WUE* g Kg ⁻¹
4/4	544.41	272.20	2.90	20	1.74
3/4	483.25	241.63	2.57	23	1.60
2/4	513.46	256.73	2.73	30	1.09
1/4	504.21	252.11	2.68	40	1.00
1/4+	619.96	309.98	3.30	27	0.72

* Seasonal WUE = New shoot biomass (g)/Total ET (Kg).

Table 4. Biomass Data of Partially Irrigated Citrus Treeings, Means and r^2 of Linear Regression of Leaf Area or Biomass Data vs Percent RVI.

	4/4 RVI	3/4 RVI	2/4 RVI	1/4 RVI	1/4+RVI	r^2
LAI $m^2 m^{-2}$	7.70	5.82	4.57	3.04	4.68	
LAI corrected	7.70	5.82	4.32	2.72	4.68	
New Leaf Area $\frac{1}{m^2 plant^{-1}}$						
Mean	0.4261	0.3341	0.1959	0.2218	0.1868	0.8679*
Std. dev.	(0.1866)	(0.1405)	(0.0937)	(0.0927)	(0.0641)	
Dry Wt. New Lvs. $g plant^{-1}$						
Mean	32.93	26.41	17.42	17.52	14.01	0.9237**
Std. dev.	(15.69)	(11.68)	(8.92)	(7.71)	(4.24)	
Dry Wt. New Shoots						
Mean	11.56	9.06	8.31	6.36	7.37	0.9291**
Std. dev.	(6.46)	(3.90)	(4.87)	(3.04)	(3.12)	
Total New Growth (leaves + shoots)						
Mean	45.00	36.92	26.56	24.03	21.38	0.9666**
Std. dev.	(22.84)	(15.49)	(14.26)	(10.32)	(6.47)	

^{1/} LAI of new leaf growth was 5.88, 4.62, 2.70, 3.07, and 2.58 for 4/4, 3/4, 2/4, 1/4, and 1/4+ RVI treatments, respectively.

* significant at $p = 0.05$

** significant at $p = 0.01$

Table 5. Mean Root Hydraulic Conductivity of Irrigated and Nonirrigated Roots of Citrus Treelings.

	ROOT TREATMENT				
	4/4 RVI	3/4 RVI	2/4 RVI	1/4 RVI	1/4+RVI
	-----mg m ⁻¹ s ⁻¹ MPa ⁻¹ -----				
	Irrigated Roots				
Mean	245.7	184.3	299.9	223.1	145.9
Std. dev.	(155.5)	(84.2)	(189.2)	(132.9)	(97.2)
	Nonirrigated Roots				
Mean	---	55.4	141.0	124.5	107.4
Std. dev.	---	(31.7)	(109.6)	(78.7)	(76.0)

Figure 1. Diurnal CER and evapotranspiration (TR) of Carrizo citrange (C) and Swingle citrumelo (S) rootstocks on 24 April 1985. ASW = 67 and 62%, respectively. Set point air temperature control was 29°C. Data are hourly averages plotted at the beginning of each hour, eastern standard time (EST).

Figure 2. Diurnal CER and evapotranspiration (TR) of Swingle citrumelo rootstocks on 25 April 1985. ASW = 26 %. Set point air temperature control was switched from 29°C to 37 °C from 1300 to 1500 (EST).

Figure 3. Diurnal CER and evapotranspiration (TR) of Swingle citrumlo rootstocks on 26 April 1985. ASW = 92%. Set point air temperature control was 29°C.

Figure 4. Diurnal CER and evapotranspiration (TR) of Swingle citrumelo rootstocks on 27 April 1985. ASW = 64%. Set point air temperature control was 29°C.

Figure 5. Soil moisture release curve of builder's sand used for growing partially irrigated citrus treeings.

Figure 6. Top: Representative diurnal CER curve of partially (3/4 RVI) irrigated citrus seedlings on 30 July 1986 with 80 % ASW. Bottom: Diurnal PAR curve for the accompanying CER curve.

Figure 7. Representative light response curve of partially (3/4 RVI) irrigated citrus seedlings on 30 July 1986 with 80 % ASW. Numbers above the data points indicate the hour during which the measurement was made.

Figure 8. Top: Representative diurnal VPD curve for partially (3/4 RVI) irrigated citrus seedlings on 30 July 1986. Bottom: DBT (open circles) and DPT (filled circles) diurnal curve for the accompanying VPD curve.

Figure 9. Representative CER response of partially (3/4 RVI) irrigated citrus seedlings to VPD on 30 July 1986 with 80 % ASW. Numbers above the data points indicate the hour during which the measurement was made.

Figure 10. Top: Diurnal VPD curve on 10 Aug 86, DBT = 33 to 37, DPT = 22°C. Bottom: Diurnal VPD curve on 28 July 86 DBT = 29 to 33 °C, DPT = 18°C.

Figure 11. Top: Diurnal CER curve for partially (3/4 RVI) irrigated citrus seedlings at high VPDs.
Bottom: Diurnal CER curve for partially irrigated citrus seedlings at low VPDs.

Figure 12. Representative diurnal CER curve for partially (3/4 RVI) irrigated citrus seedlings on 19 August 1986 at an elevated CO_2 concentration ($880 \mu\text{mol mol}^{-1}$).

Figure 13. Representative ET curve for partially (3/4 RVI) irrigated citrus seedlings on 30 July 1986 with 80 % ASW.

Figure 14. Representative WUE curve for partially (3/4 RVI) irrigated citrus seedlings on 30 July 1986 at ambient CO_2 concentration ($340 \mu\text{mol mol}^{-1}$) and 80 % ASW.

Figure 15. Representative WUE curve for partially (3/4 RVI) irrigated citrus seedlings at an elevated CO_2 concentration ($880 \mu\text{mol mol}^{-1}$) on 19 August 1986.

Figure 16. Daily total ET values for partially irrigated citrus during the initial ten days of the 1986 study.

Figure 17. Diurnal CER curve for partially irrigated citrus on 1 August 1986 at similar levels of ASW.

Figure 18. Diurnal VPD curve for partially irrigated citrus on 1 August 1986.

Figure 19. Diurnal ET curves for partially irrigated citrus on 1 August 1986 at similar levels of ASW.

Figure 20. Diurnal WUE curves for partially irrigated citrus on 1 August 1986 at similar levels of ASW.

Figure 21. Diurnal CER curves of partially irrigated citrus with St. Augustine grass cover (1/4+) and without grass cover (1/4) on 28 June 1986.

Figure 22. Diurnal ET curves of partially irrigated citrus with (1/4+) and without grass cover (1/4) on 28 June 1986.

Figure 23. Diurnal WUE curves of partially irrigated citrus with (1/4+) and without grass cover (1/4) on 28 June 1986.

Figure 24. Diurnal CER curves of partially irrigated citrus with St. Augustine grass cover (1/4+) and without grass cover (1/4) on 26 July 1986.

Figure 25. Diurnal ET curves of partially irrigated citrus with (1/4+) and without grass cover (1/4) on 26 July 1986.

Figure 26. Diurnal WUE curves of partially irrigated citrus with (1/4+) and without grass cover (1/4) on 26 July 1986.

Figure 27. Mean new leaf area of partially irrigated citrus seedlings on Carrizo citrange, Swingle citrumelo, and Sour orange rootstocks.

Figure 28. Mean dry weight of new leaves of partially irrigated citrus seedlings on Carrizo citrange, Swingle citrumelo, and Sour orange rootstocks.

Figure 29. Mean dry weight of new stems of partially irrigated citrus seedlings on Carrizo citrange, Swingle citrumelo, and sour orange rootstocks.

Figure 30. Mean dry weight of new shoots (leaves + stems) of partially irrigated citrus seedlings on Carrizo citrange, Swingle citrumelo and Sour orange rootstocks.

Figure 31. Mean dry weight of roots (old + new) of partially irrigated citrus seedlings on Carrizo citrange, Swingle citrumelo, and Sour orange rootstocks.

APPENDIX A

Table A1. Schedule of citrus establishment and treatments.

Date	Event
16-22 Aug 85	Acquired citrus treelings. Pruned roots and placed treelings in rooting trays to establish split-root system.
15 Feb 86	Began transferring citrus trees from the rooting trays to split-root containers.
01 May 86	St. Augustine grass seed planted in 21 containers.
25 May 86	Harvested 6 plants for evaluation of split-root technique.
14 Jun - 03 Aug 86	Citrus trees placed in all SPAR chambers. Environmental control setpoints: DBT = 29/25 °C (day/night) DPT = 18/14 °C CO ₂ = 340 µmol mol ⁻¹
14-24 Jun 86	Citrus treelings maintained under well irrigated conditions, i.e., irrigated in all compartments of containers.
25 Jun 86	Initiated partial irrigation treatments.
04-10 Aug 86	Environmental control setpoints: DBT = 37/25 °C DPT = 22/14 °C CO ₂ = 340 µmol mol ⁻¹
11-19 Aug 86	Environmental control setpoints: DBT = 37/25 °C DPT = 22/14 °C CO ₂ = 880 µmol mol ⁻¹
20-25 Aug 86	Environmental control setpoints: DBT = 29/25 °C DPT = 18/14 °C CO ₂ = 880 µmol mol ⁻¹
26 Aug - 13 Oct 86	Environmental control setpoints: DBT = 29/25 °C DPT = 18/14 °C CO ₂ = 340 µmol mol ⁻¹
15 Sep 86	Began removing plants from SPAR chambers for biomass and root hydraulic conductivity measurements.
13 Oct 86	Finished sampling plants; all plants removed from chambers.

Table A2. Irrigation (I)/Fertigation (F) of split-root citrus,
16 Jun - 15 Sept, 1986.

Date	Rooting Volume Irrigated (RVI)				
	1/4+	1/4	2/4	3/4	4/4
16-Jun-86					F
17	F	F	F	F	
19		I	I		I
20	I			I	
22	F	F	F		
23				F	F
24		I			
25		I			
26	I		I		
27		I		I	
29		F	F		
30				F	I
01-Jul-86	I	I			
02			I	I	
03		I			
04	F		F		
05		F			
07	I	I	I	I	I
08	F	F	F	F	F
10		I			
11			I		
12	I	I			
13				I	
14		I	I		I
15	I				
17		F	F		
18	F				
19				F	F
21	I	I	I	I	I
23		I			
24	I				
26		F	F		
27	F				
28		I		I	I
29			I		
30		I			
31	I				
01-Aug-86			I	I	
02		F			
03					F
05	F	F		F	
06			F		
07	F	F	F	F	F
09		I			

Date	Rooting Volume Irrigated (RVI)				
	1/4+	1/4	2/4	3/4	4/4
10-Aug-86			I		
11		I		I	I
12	I		I		
15	F	F	F	I	
17					I
19	I	I	I		
21			I	I	
22		I			
23	I				I
24		I			
25			I	I	
27	F	F		F	
28		I			F
29			F		
31	I	I			I
01-Sep-86			I		
02		F			
03				I	
04	F		F		
05		I			
06	I	I		I	I
08	I	I	I	I	
09					I
10		I	F		
12	F		I		
13		F			I
14				I	
15		I

Figure A1.

SPECIFICATIONS: SPLIT ROOT PLANTER

OVERALL DIMENSIONS (see diagram):

Height: 587 mm (23.1 inches)
Length: 400 mm (15.75 inches)
Width: 150 mm (5.9 inches)

INDIVIDUAL COMPARTMENT DIMENSIONS (see diagram):

Height: 500 mm (19.7 inches)
Length: 200 mm (7.875 inches)
Width: 75 mm (2.95 inches)

POT RECESS will be provided at the top junction of the 4 compartments as shown in the accompanying diagram.

FLANGES of the outside face of each compartment must be 13 mm (0.5 inches) so that the purchaser can install plate glass fronts for observation of roots (Plate glass is not a part of this specification.)

MATERIALS:

1. PLANTER WRAPPER to be of 22 Ga. Galvanized Steel, Height = 587 mm (23.1 inches), Length = 400 mm (15.75 inches), Width = 150 mm (5.9 inches).
2. PLANTER DIVIDERS to be of 20 Ga. Galvanized Steel, 500 mm (1.97 inches) in Height.
3. DRAIN ASSEMBLY to be of Stainless Steel consisting of 1/2" Nut and 1/2" x 1/2" Allen Screw.

FABRICATION:

1. DRAINS: Tack weld stainless nut into alternated corners inside planter as indicated on drawing. The drain hole is to be punched with a 1/2" I.D. minimum diameter.
2. DIVIDER PANELS are to be spot welded in place running the entire length of the planter for maximum internal support.
3. JOINTS: The 13 mm (0.5 inch) flanges will have glass mounted against them, thus the vertical side must lap to the outside of the bottom horizontal flange. These vertical sides will be mitred to minimize sharp edges.
4. ANGLES are right angles (90 Degree) to facilitate installation of glass faces.
5. POT RECESS will be provided for planting pots at the confluence of the planter's dividers measuring 76 mm (3 inches) deep, 127 mm (5 inches) wide at the top and 108 mm (4.25 inches) wide at the bottom as illustrated in Diagram.
6. HAND HOLES will be 102 mm (4 inches) long with a 38 mm (1.5 inches) radius at each end with 13 mm (0.5 inch) hem to minimize sharp edges.
7. PROTOTYPE of a model correct except for dimensions can be provided as a guide to the vendor.

Figure A3. A side view schematic of an environmentally controlled plant growth chamber and associated ductwork. The chamber is subdivided into 10 numbered compartments, each containing control elements, sensors or other key system components. Air circulates into the growth chamber from the upper duct (10) and exits into the lower duct (3).

Figure A4. Diurnal CER of partially irrigated citrus on 4 July 1986.

Figure A5. Diurnal ET of partially irrigated citrus on 4 July 1986.

Figure A6. Diurnal WUE ($\mu\text{mol CO}_2 / \text{mmol H}_2\text{O}$) of partially irrigated citrus on 4 July 1986.

Figure A7. Diurnal CER of partially irrigated citrus on 26 July 1986.

Figure A8. Diurnal ET of partially irrigated citrus on 26 July 1986.

Figure A9. Diurnal WUE of partially irrigated citrus on 26 July 1986.

Figure A10. Diurnal CER of partially irrigated citrus on 4 September 1986.

Figure A11. Diurnal ET of partially irrigated citrus on 4 September 1986.

Figure A12. Diurnal WUE of partially irrigated citrus on 4 September 1986.

DESCRIPTION OF COOPERATION

The principal investigators have kept in contact regularly by letter and through electronic exchange of information. They met in the USA at national meetings in Chicago, Illinois, in 1985. Dr Y. Cohen visited the laboratories in Gainesville in the summer of 1986 to discuss the contribution of the heat pulse method to the evaluation of transpiration in citrus trees. The principal investigators met again in Gainesville, Florida, in 1987. They analyzed their results comparing the field experiments to the work which was carried out in growth cabinets and agreed upon the way of representing the final report.

EVALUATION OF RESEARCH ACHIEVEMENTS

The controlled environment studies in Florida and the field studies in Israel investigated the effect of cycling the volume of wetted roots on citrus tree activity from several aspects; plant and water relations, water loss, reproduction and production and photosynthesis. The hypothesis was that the periodic cycling of the active root volume which is controlled by wetting and drying part of the soil is stressing the citrus trees.

The Israeli party found that root growth was reduced by drying part of the soil but a seasonal cycling of the drought did not have a considerable effect on the trees. Yields were similarly reduced by all partial soil wetting treatments relative to a complete soil wetting treatment. The fractional drop in yield was smaller than the fractional gain in applied water. It was shown that the threshold soil water potential which control the response is high (15 to 20 kPa).

Short and long term effects of root pruning on water stress were studied in the mature trees. It was shown that root length may be reduced with minor effects on stress. The seasonal cycling effect is also minor. On the other hand, stress develops faster when roots are shorter.

The results of the Floridan study imply that citrus seedlings grown on soils with low water holding capacities and irrigated with low volume irrigation systems which wet only a portion of the entire root volume will suffer a reduction in photosynthetic rates that will result in diminished plant growth. There is evidence that citrus on Swingle citrumelo rootstocks are less detrimentally affected by reduction of the volume of irrigated tooting zone than plants on either Carrizo citrange or Sour orange rootstocks. This study also reveals no advantage in terms of reduced water use, increased plant growth or improved water use efficiency of citrus when partially irrigated citrus are

grown with a grass cover. In fact, grass cover seems to impart disadvantages.

Because of the short term nature of the Floridan study, extrapolation of the results to a long term practice in the field is difficult. Plants in this study were unable to regrow completely an adequate amount of roots to replace those lost by reducing the irrigated soil volume.

Detailed measurements were obtained of whole-plant photosynthetic and transpirational response, stomatal conductance, root hydraulic conductivity, shoot and root growth and water use when 100, 75, 50 or 25 % of the rooting volume of citrus treeings was irrigated. This fulfilled the primary goal of the first objective of the USA portion of this study. The study successfully adapted a method for establishing citrus treeings with 4-part split-root systems and demonstrated it as a practical system with which partial rooting volume irrigation effects can be studied.

The conditions under which this study was conducted, specifically the use of a growing medium with low water holding capacity and irrigation scheduling when $2/3$ of the plant available soil water had been depleted, were not described in the original research proposal, but were appropriate for studying citrus response to partial root zone irrigation under conditions similar to those under which it is grown in Florida. This study also provided insights into the interacting effects of limiting soil water availability and atmospheric evaporative demand on citrus water status and photosynthesis.

The objective to adapt existing plant-water flow models to predict citrus water stress, stomatal response, and photosynthesis under partial rooting volume irrigation, has not been completed. A phenomenological model to predict the capacity of reduced volume of actively transporting citrus roots to supply adequate amounts of water to meet

transpirational demand when grown on soils with high or low water holding capacity and under conditions of high or low atmospheric evaporative demand is currently in progress. The results of this work will be presented in the Ph.D. dissertation of Mary Brakke and made available to BARD.

PUBLICATIONS

Moreshet, S., Y.Cohen and M. Fuchs. 1988. Water use and yield of a mature Shamouti orange orchard submitted to root volume restriction and intensive canopy pruning. pp 41-48 in Proc 6th int Citrus Congress, Tel Aviv. Eds R. Goren and K. Mendel.

Allen, L.H., Jr., M.P. Brakke and J.W. Jones. 1985. Climate, soil water and CO₂ effects on citrus seedling photosynthesis and transpiration. American Society of Agronomy Abstracts. 76:10.

Brakke, M.P., L.H. Allen, Jr., and J.W. Jones. 1986. Effect of partial root-volume irrigation on photosynthesis and transpiration of citrus seedlings. American Society of Agronomy Abstracts. 77:12.

In Preparation:

Brakke, M.P. 1988. Citrus seedling response to partial root zone irrigation and atmospheric variables. Ph. D dissertation, University of Florida. (A copy will be made available to BARD).

Several journal articles that will include material presented at the American Society of Agronomy meetings in 1985 and 1986.