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Optimization of Water and Nitrogen Application by Automated Drip Irrigation Control for Apple Trees

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Abstract

Four irrigation treatments applied at the rate of consumptive use were studied in an apple orchard located in the Hula Valley of Israel. These irrigation treatments were compared with two other treatments based on class A pan evaporation coefficients and neutron probe measurements. The irrigation at the rate of consumptive use was carried out by a system consisting of SMP sensors located at 30 and 35 cm horizontal and vertical distance from the tricklers and an automated trickle irrigation system controlled and actuated by a computer. Signals of 3 to 4 sensors for each treatment were averaged in order to turn on the irrigation at a predetermined SMP threshold. The irrigation was applied in 10 minute on and off pulses to minimize overshooting of the SMP. Two kinds of tensiometers were studied; electrotensiometers generated a continuous signal and heat dissipation sensors (Phene type) programmed to generate a signal every 20 minutes. The treatments consisted of two different thresholds for each sensor type and produced two different volumes of irrigated soil and two different rates of water uptake at various distances and depths in relation to the tricklers. A model was developed for predicting the rates of SMP changes. The good agreement between the predicted and measured values promises efficient means for locating the sensors in future applications. The low SMP threshold treatment which was maintained at -25 and -15 kPa for three successive years showed the expected results. Compared to treatments which were irrigated according to neutron probe measurements, pan evaporation coefficient or automated SMP threshold of -10 kPa - the lower SMP threshold trees showed the following effects: Reduced water requirement, reduced volume of irrigated soil and reduced vegetative growth and fruit yields. However in the third year fruit size was not impaired and the crop load was not affected in Jonathan and slightly increased in Golden

✓ Delicious. This typical effect of restricted root system is expected to allow more trees per ha, better light penetration for quality fruit, reduced cost of orchard operations, increase in fertility and crop load without reducing fruit size.

Abbreviations

SMP - Soil matric potential

T₁₋₆ - Treatment 1-6.

TSS - Total soluble solids

G.D. - Golden Delicious

J. - Jonathan

OBJECTIVES OF ORIGINAL RESEARCH PROPOSAL

The objectives of this research project were to determine the consumptive rate of water for optimal apple production and to develop and test an automatic monitoring and control system for applying water at consumptive use rates of apples and other fruit trees. (The third objective concerning mineral nutrition control was not approved by BARD).

Introduction

In order to optimize the production of fruit trees it is necessary to apply water and minerals at the rate of consumptive use. This will ensure that the trees are not subjected to either an excess or deficiency of water or minerals and that no waste will occur. It should be borne in mind that the rate of consumptive use is not necessarily dependent on the tree itself but can also be imposed by the grower since plants are capable of adjusting themselves to various irrigated soil volumes and levels of soil matric potential (SMP) in the irrigated zone. The adjustment is expressed in the amount and rate of vegetative growth and in the yield produced (Middleton and Proebsting 1979; Proebsting et al. 1977; Assaf et al. 1974; Levin et al. 1980; Elfving, 1982).

Drip irrigation is the most appropriate method for irrigating at the rate of consumptive use because of its slow rate of water emission. Fertigation by drip at the rate of consumptive use forms a constant and a restricted volume of irrigated soil as well as constant gradients of water, minerals and aeration within it. The root system adjusts to that irrigated volume and roots outside the wetted zone do not function but do survive even in dry soils. These roots may become reactivated when the soil is wetted again.

Drip irrigation is the main method used for irrigating apples in Israel. Its technical and cultural advantages are widely recognized but the physiological advantages have not yet been fully explored.

The expected physiological effects are as follows: (a) Restricted root volume is known to cause dwarfing and to increase the ratio of reproductive to vegetative growth (Richard and Row 1967; Salomon, 1979; Moss, 1978; Lenz, 1967). This may allow more trees to be planted per ha, precocity, reduce agrotechnical operation costs, and increase light penetration into the canopy, thereby improving fruit quality. Drip irrigation may replace the

use of dwarfing rootstocks in areas with dry summers. (b) It is well established that plants grown under controlled conditions respond to concentrations of water and minerals rather than to amounts. Thus the methodology used in this project allows for the application of principles used under controlled conditions to field-grown plants. (c) Improvements in yield and fruit quality may be achieved through controlling SMP levels and mineral concentration at various stages of growth and development. The objectives of this research was to study the effect of various irrigated soil volumes and SMP levels, on growth yield and fruit quality of apples, while applying irrigation at the rate of consumptive use. The application of automated irrigation treatments control by SMP sensors located at a constant depth and distance from the emitters and operated by a computer provided means for irrigating the rate of consumptive use.

✓ MATERIALS AND METHODS

The experiment was conducted at Ayelet Hashahar in the southern part of the Hula Valley of Israel. The soil is a brown alluvial vertisol, uniform down to 1.5 m, with an underlying layer of calcareous gravel. The soil texture is 69% clay, 25% silt and 6% sand; pH (in water) is 7.6, bulk density 1.4, field capacity 39% and wilting point 26% (by weight).

The apple cvs Golden Delicious and Jonathan, on selected Hashabi rootstock (medium vigor), were planted in 1971 at 4 x 3 m spacing. Additional pollinators were cvs Orleans and Granny Smith. Fertilizers were applied through the irrigation system at ca. 320 kg N ha⁻¹, 450 kg K ha⁻¹ and 30 kg P ha⁻¹ (every three years) and 5 kg ha⁻¹ of Sequestrene H138 annually.

The soil water retention curve and its hydraulic conductivity as a function of the volumetric soil water content (θ) were determined in the laboratory and are presented in Figures. 1 and 2. The available NPK content of the soil was analyzed twice a year at different distances from the emitter at depths of up to 60 cm. Since no significant differences in NPK levels between the specific treatments were found, we present the average data of all treatments for the 0-60 cm soil layer (Table 1). The levels of NPK were within the normal range for good commercial apple orchards and there was no evidence of nutritional limitations for any of the various irrigation treatments.

The 6 treatments were arranged at random in four blocks with 14 trees per replicate. Details of treatments are given in table 2.

Three types of automated irrigation were examined: 1. Irrigation actuated by electrotensiometers for controlling the SMP levels in the root zone. 2. Irrigation actuated by heat dissipation sensors (Phene type) (Phene et al. 1971, 1971) for controlling SMP levels in the root zone.

3. Automated pan evaporation.

All three types of automated irrigation were connected to a computerized control unit (PCU 10, Motorola, Israel). Irrigation in each treatment was controlled by 4 sensors, one per replicate. The electrotensiometers were constructed of regular tensiometers (AMI Ltd., Israel and Irrrometer Co., USA) equipped with electronic vacuum transducers (Motorola Co., USA) which were connected to the computer. The electrotensiometers produced continuous signals proportional to the pressure inside the tensiometers. The heat dissipation sensors (Agwatronics Co., USA) measure the SMP by recording the heat dissipation in a porous ceramic body, which is in equilibrium with the SMP of the soil and is operated by the computer.

In addition regular tensiometers were placed at similar distances and depths from the drippers to enable monitoring of the automatic SMP readings of the electrotensiometers and heat dissipation sensors. Good agreement was found between these manual recordings on the regular tensiometers and the computer-recorded readings of the electrotensiometers (data not shown).

For each treatment the data obtained from the 4 sensors were averaged by the computer for each treatment. The sensors were positioned 30 cm and a depth of 35 cm from the dripper. This position was selected after preliminary trials. Irrigation was applied in on and off pulses of 10 minutes in order to minimize overshooting of the SMP level following the off signal. The electronic circuit of the system is presented in Fig. 3. The automated evaporation pan was also connected to the central computer and was set to irrigate according to varying coefficients during the season. Each pulse was given after 1 mm of water had evaporated from the pan. Results of the automated pan are not presented in this report since the system came into effective operation only at the end of the 1985 season.

The non-automated irrigation treatments were also operated by the computer. Irrigation in these treatments was performed daily by programming

the computer to apply water amounts based on pan evaporation (Fig. 11) (two different coefficients) and on soil moisture neutron probe measurements (Table 2). The neutron probe measurements (Ronly electronics, Israel) were conducted twice a week. The access tubes were located at horizontal distances of 20, 35, and 70 cm from the drippers. The readings were taken at 30 cm increments down to a depth of 90 cm. The amount of irrigation water in the plots irrigated according to neutron probe readings was calculated so as to maintain a constant average soil water content close to field capacity at a distance of 35 cm from the dripper and in a profile of 0-60 cm deep. The experiment was planned to start in 1982, but was unavoidably delayed both because of the need to install an underground long-distance electrical cable and on account of the 1982 war situation. The setting up of the electronic units in the field and the acquisition data computer unit were therefore completed only at the end of the 1982 season and the experiment commenced in the spring of 1983. During that year only the two electrotensiometer treatments were in operation, while the heat dissipation sensors were still under calibration. In the 1984 season the SMP threshold electrotensiometer settings were changed from -10 and -25 to -5 and -15 kPa and one of the 75% pan evaporation treatments was changed to neutron probe controlled irrigation. In 1985 the SMP threshold settings of the electrotensiometer treatments were changed to -10 and -15 kPa. A new version of the heat dissipation sensors was operated at the same SMP thresholds as the electrotensiometers. The pan evaporation and neutron probe controlled treatments were continued, as detailed in Table 2.

The circumference of each tree-trunk was measured with a tape at a fixed point 20 cm above the ground each winter. The rate of fruit growth was measured weekly with a plastic measuring tape on 8 carefully selected fruit growing on equal-sized spurs evenly distributed around the tree (128 fruit per treatment). Fruit dropped during the season (ca. 10%) were discarded.

The volume of the fruit of each cultivar was calculated from the circumference measurements according to previously published data (Assaf et al. 1982). Leaf water potential was periodically measured by pressure chamber. Transpiration and stomata resistance were measured using a ventilated diffusion porometer (Cauga development) (Bravdo 1972).

The yield in each treatment replicate was weighed and the fruit size distribution recorded. The quality (firmness, acid and TSS content) of the fruit in each replicate was determined at harvest.

The mineral content of the leaves and of the whole fruit was analyzed several times during the year.

Theoretical Approach For Determining SMP vs. Time In Orchard During Drip Irrigation Cycles Controlled Automatically By SMP Sensors

Quantitative estimation of changes in the soil water content or SMP levels in the plant root zone during the irrigation cycle is of great practical importance. Models based on soil characteristic data, assumptions of the distribution and the water uptake rate of plant roots are reported in the literature (Bresler, 1978; Fok, 1982; Molz and Remson, 1970; Hanks and Bowers, 1982; Nimah et al. 1979). Using the relevant soil and plant data from our experiment and some simplified assumptions based on existing models, enabled to estimate changes in SMP levels during irrigation cycles for various SMP sensor locations and thresholds.

The resulting computed data showed in some cases a good agreement with the actual data determined in the orchard. These preliminary results indicate that after model is improved and possibly modified it should be possible to use it for determining the influence of location and SMP threshold of the sensors in optimizing irrigation efficiency.

Input Data Used For The Simulation Program

The basic assumptions for the water extraction rate pattern were

(according to Molz and Remson, 1970):

$$S(z) = -\frac{1.6 T}{V^2} Z + \frac{1.8 T}{V} ; \int_0^V S(z) dz = T$$

S - moisture extraction rate per unit volume of soil

T - transpiration rate per unit soil surface area

Z - depth below soil surface

V - depth of root zone.

Assuming a radial root and water distribution we substituted Z for r (radial distance from the emitter) and V for maximal root zone radius.

The hourly transpiration rate was calculated by assuming a sinusoid daily pattern (Dendorff, 1978):

$$A = B \sin\left(\pi \frac{T}{12}\right)$$

A = hourly transpiration rate

B = maximum hourly transpiration rate (an empirical parameter dependent on the day in the season on pan evaporation; B=A at midday)

T = hour of the day (T = 0 at 6 am and T = 12 at 6 pm)

For input data the daily transpiration rate was taken as 0.7 cm/day and the maximum hourly transpiration rate was accordingly 0.09 cm.

Under conditions of limited soil volume caused by SMP sensor actuated automated irrigation, a ratio of $\frac{60 \text{ cm}}{400 \text{ cm}} = 0.15$ was used (60 cm - radial water distribution and 400 cm = row spacing) for calculating the water extraction rate per unit soil volume. The programme takes into account that the water loss by drainage and transpiration is equal to the difference in the volumetric soil water content adjacent to the emitter.

The drainage below the root zone was calculated (according to the hydraulic conductivity at the specific soil water content (K_θ)). The soil water content was converted to SMP using the retention curve. When the SMP reaches the pre-set threshold, the water supply is initiated. The progress of the wetting front is calculated from data of K versus θ and θ_{max} , SMP

vs. θ and dripper discharge rate using equations described by Fok, 1982. The transpiration occurring simultaneously with irrigation is deducted step-wise and actually appears as increase of time of the water movement to the sensor. When the wetting front reaches the sensor the water flow from the dripper stops and the water uptake due to transpiration continues.

The computer output data appear as hourly SMP values during a 24-hr irrigation cycle at the location of the sensor. Examples of results of these data in two SMP thresholds at the same sensor location relative to the dripper are presented in Figures 6 and 7.

The use of the simulation technique described has advantages for the evaluation and estimation of the effect of different positioning of the sensors in relation to the dripper and the effect of threshold setting on the SMP fluctuations and levels during the automated irrigation process. There are of course some shortcomings, and one could improve the model by taking into account the sensitivity lag-time of the response of the sensors to the soil water content changes. Work on improving the model is continuing. However, the good agreement between the output results and the recorded data (Figs. 6,7) promises useful application in the near future.

RESULTS AND DISCUSSION

Control of SMP by the automated irrigation systems

Results in 1983

In 1983 only electrotensiometers were used for SMP control. The threshold settings were -10 and -25 kPa for T_1 and T_4 respectively. These SMP levels required 741 mm of total seasonal water for T_1 and 638 mm for T_4).

Figures 4 and 5 show some examples of daily changes in SMP levels with T_1 and T_4 . It can be seen that the SMP level varied between -5 and -14 kPa in T_1 and between -15 and -26 kPa in T_4 . In both treatments, irrigation

commenced at precisely the predetermined threshold values programed into the computer. Overshooting during the wetting cycles occurred inspite of on-off pulsing for 10 minutes in both treatments. It is also interesting to note that the values recorded on the elctrotensiometers continued to increase after the commencement of each irrigation, particularly in T₁. On most days the increase in SMP started at noon, causing irrigation to begin in the evening. Observations of pan evaporation (not shown) showed that the rate of evaporation was higher in the afternoon than in the morning. It is not clear whether and to what extent the fluctuations in SMP level were due to phenomena such as water redistribution or time-lags found as a result of limitations of the hydraulic conductivity rate of the soil. Fluctuations and overshooting of this kind maybe reduced or even eliminated by locating the sensors closer to the water emitters, or by extending the intervals between irrigations.

Results in 1984

In 1984, again only electrotensiometers were used for SMP control. The threshold settings for irrigation were changed to -5 and -15 kPa for T₁ and T₄ respectively. These SMP levels required 725 mm of seasonal water for T₁ and 689 mm for T₄. The SMP in T₁ varied between -1 and -10 kPa, while the starting and closing of irrigation occurred mostly between -5 and -7 kPa (Figs. 6,7). In T₄ the SMP varied between -8 and -16 kPa, while the starting and stopping occurred mostly at -15 and -16 kPa (Figs. 6,7). The increase in SMP in both treatments started mostly at noon time and irrigation began in the late afternoon, similar to the pattern in 1983.

Results in 1985

By 1985 both irrigation control systems, i.e. of electrotensiometers and heat dissipation sensors, were in use. The threshold settings were -10 and -15 kPa both for T₁ and T₄ (electrotensiometers) respectively and for T₂ and T₆ (heat dissipation sensors) respectively. These SMP levels required 722

and 617 mm of seasonal water for T₁ and T₄ and 742 and 653 mm for T₂ and T₆ respectively. The SMP levels varied mostly between -6 and -14 kPa for T₁ and between -8 and -18 kPa for T₄ (Figs. 8,9). For T₂ and T₆ (heat dissipation sensors) the SMP levels varied mostly between -6 and -16 kPa and between -10 and -17 kPa, respectively (Fig. 10). As shown the starting and stopping of the irrigation are in good agreement with the preset SMP threshold values. Figures 8 and 9 (electrotensiometers) show that in July 1985 irrigation began at noon and that occasionally there were two irrigation cycles per day. In the heat dissipation sensor treatments irrigation started mostly at night and stopped during the morning (Fig 10).

Irrigation regimes and soil water content

The different treatments applied caused substantial differences in seasonal water amounts. In T₂ and T₃ during the first two years the water application rate was selected according to the usual recommendations based on pan evaporation coefficients at the different growth stages (Table 3). The pan evaporation coefficients used were 0.5 during first period until (mid-June), 0.9-1.0 during the second period (until the harvest) and 0.5 or less during the other periods. It was under this schedule that the largest amounts of water were applied. In the two treatments in which irrigation was actuated by the electrotensiometers, the water amounts were always higher in T₁ than in T₄ (by ca. 13%) because of the difference in the SMP thresholds. It is interesting to note that in T₁, the automated irrigation procedure with the higher SMP level the water application rate in each of the three years of the experiment was lower than in the treatments during 1984 based on pan evaporation coefficients or on the neutron probe. A possible reason for this lower rate is the reduction in water loss due to percolation to layers below the root zone, a phenomenon known to occur in drip irrigation (Levin et al. 1979).

A similar reduction in water amount occurred in 1985, with T₂, where the

irrigation was actuated by heat sensors with a high SMP threshold. In the same year irrigation in T₆ was actuated at the lower threshold (equal to that in T₄), and this resulted in an appreciable reduction in water amount (Table 2).

In 1983 the soil moisture content distribution at different depths and distances from the tricklers as measured by neutron probe is shown in figures 12-17. T₃, which was irrigated according to the pan evaporation had the highest soil moisture contents during June and half July, particularly in the 60-90 cm layer at 35 cm distance from the emitter (Figs. 12, 13). The 30-60 cm layer both in T₁ and T₃ had similar moisture content at the 35 cm distance, however at 70 cm distance T₃ was higher in moisture content at both 0-30 and 60-90 cm depth. This indicates that T₁ which was irrigated by the automated computerized system, had a smaller volume of wetted soil as compared to T₃ which was irrigated according to the class A pan evaporation. The difference between these two treatments became smaller in August, indicating probably that the rate of consumptive use as determined by the sensors was similar to that determined by the pan evaporation coefficient. Treatment 4 which was irrigated by the sensors with threshold values of -25 kPa had lower soil moisture content at all depths and distances from the tricklers, as compared to T₁ and T₃ (Figs 12-17).

In 1984, the distribution of water content at varying soil depths and at different distances from the dripper shows that where the amounts of water applied were high (in T₂ and T₃), the water content at a distance of 70 cm over the whole depth profile was higher than in treatments where less water was applied T₁, T₄, T₅ and T₆. However, the water content at distances closer to the dripper (20 and 35 cm) was quite constant and remained high in all treatments. This indicates that by irrigating automatically according to SMP level, smaller soil volumes are wetted and less water is applied than in the case of the commonly recommended irrigation schedules. In the

treatment irrigated daily according to neutron probe measurements (T₅) the amount of water applied (849 mm) was intermediate between the amounts applied in the pan evaporation (T₃) and the automatically irrigated treatments T₁ and T₄ (910 and 700mm respectively). The larger amounts of water resulted in higher soil water content at a distance of 70 cm from the dripper, while smaller amounts resulted in a lower soil water content (Tables 2, 3; Figs. 18-23).

In 1985 the soil water content, for T₁ and T₂ were similar, and were higher at distances of both 35 and 70 cm than for T₄ and T₆ were lower lower SMP levels were maintained (Figs. 24, 25 and 26). These treatments, of course, differed with respect to the total water applied (Table 2). T₃, which was irrigated in this year according to neutron probe measurements, was better balanced than T₅, which was irrigated at the basis of pan evaporation coefficients. This is reflected in the more uniform soil water content at a distance of 35 cm and the higher water content at a distance of 70 cm for T₃, despite the fact that less water was applied here than in the case of T₅. The soil water contents for T₁, T₂ and T₃ were similar at distances of both 35 and 70 cm from the dripper, indicating that maintenance of a constant SMP level results in higher water use efficiency than is obtained when irrigating according to pan evaporation coefficients, when more water is probably lost through percolation below the root zone.

We conclude that irrigation according to SMP level seems to result in the efficiency of water use by decreasing the percolation loss and less variation from year to year in soil water distribution. The results show clearly that different levels of SMP have an influence on the irrigated soil volume and its water content.

Physiological measurements

The stomatal resistance and leaf temperature of T₄ were the highest among

the treatments during the season between June 25 and October 15 1984 (Table 4). The average values of leaf water potential during 1984 were around -2 MPa at noon time and no significant differences between the treatments were apparent (not shown). No significant differences in transpiration and in leaf resistance were observed in the morning hours, whereas between 10 and 12 am when the evaporative demands were increased the leaf resistance of T₄ was significantly higher (Table 5). Transpiration was decreased and leaf resistance increased after harvest probably due to the effect of fruit removal (Table 6).

The physiological data show that T₄ maintained a normal water potential probably due to restricting transpiration by closing the stomata.

Yields, growth, quality and composition of fruit

The yields for all treatments in both cultivars were relatively high, the fruit were large and their quality was good (See Tables 7,8) throughout the experimental period. Annual yields for all treatments of 90 t/ha for Golden Delicious and 60 t/ha for Jonathan were achieved due to the intense cultural practices applied in this orchard since planting. Daily drip irrigation, fertilizing with high NPK, dense planting and the modified palmetta training system were the main characteristics of this intensification.

In spite of the differences in water regimes during the three years of the experiment, only T₄ resulted in significantly lower yields and growth compared to the rest of the treatments (Tables 7,9). However, the difference was significant only for the averages taken over three years and not for individual year. This may be explained by the slow response of fruit trees to such treatments; longer periods are probably needed in order to conduct studies of that kind. Due to the technological obstacles which encountered, only T₁ and T₄ showed consistent differences in SMP levels which were maintained throughout the entire experimental period. This

resulted in significant differences in yield and growth between these two treatments. The differences were reflected in both fruit number and fruit size (Tables 7,8). Although the results for 1982 are not presented here due to difficulties described above, it should be mentioned that T₁ and T₄ were both in operation during that year, and used different total water amounts. This may explain the smaller number of fruit obtained with T₄ in 1983 (Table 7).

In Golden Delicious, the fruit size, for T₄ was considerably smaller than for T₁ in 1983. The difference narrowed from year to year and in 1985 almost equal fruit sizes were obtained for both treatments (Table 8). The number of fruit per hectare for T₄ was considerably lower than for T₁ in 1983, and almost equal in 1984 and again lower in 1985. The smaller yield for T₄ than for T₁ was due to both size and number of the fruit in 1983, due size only in 1984 and to number only in 1985 (Tables 7,8). Trunk growth was consistently and significantly smaller for T₄ than for T₁ in all three years. The fruit load for T₄ (expressed as kg of fruit per cm² trunk increment per tree) was equal to that of T₁ in 1983 and higher than that of T₁ in both 1984 and 1985. We therefore conclude that the vegetative growth of the trees, as reflected in the trunk growth in T₄ was more severely impaired than the reproductive growth as reflected in the number of fruit. This means that the restricted volume of irrigated soil in T₄, which was probably followed by root restriction lead to the expected result: an increase in the ratio of reproductive to vegetative growth. The immediate response of root restriction in 1983 was a severe reduction in fruit size and number and in vegetative growth, with no effect on fruit load. In 1984 the fruit size was reduced due to the increase in fruit load, whereas in 1985 a good balance seems to have been achieved at a fruit load ratio of 8.3, as indicated by the fruit size, which was large and similar to that obtained with T₁ (Table 8).

In Jonathan, the fruit size for T₄ was considerably smaller than for T₁

in 1983, but the difference narrowed consistently over the three year period from 0.43 to 0.2 to 0.1 cm (Table 7). The number of fruit per hectare was lower for T₄ than for T₁ in each of the three years of the experiment (Table 7). The lower yield for T₄ each year was on account of both fruit size and fruit number, but the relative contribution of fruit size to this low yield diminished each year. Trunk growth was considerably and significantly smaller for T₄ than for T₁ in 1983 and 1984 and slightly smaller in 1985 (Table 8). We therefore conclude that root restriction had a similar affect on both growth and yield in Jonathan. The implication is that root restriction in T₄ had less positive effects than in Golden Delicious but was still good enough to be justified. Root restriction makes it possible to increase the number of trees per hectare, due to their smaller growth without impairment in productivity. Moreover, one may expect better fruit quality because of improved light penetration, as well as costs of cultural practices such as picking, pruning and spraying. The difference in response between Golden Delicious and Jonathan may be attributed to the relatively lower productivity of Jonathan as expressed in fruit load ratios. It may be that the response of Jonathan is naturally slower and requires a longer period in order to be expressed. Support for this suggestion comes from the consistent increase in fruit size (Table 8).

Treatments 2 and 6, i.e those in which irrigation was controlled by heat dissipation sensor, came into operation only in 1985. It is therefore not surprising that no significant differences between them were found in any of the plant parameters measured.

The rate of growth in apple volume as presented in Figs 27-32, is a good indicator of the appropriateness of irrigation. Water deficits were found to cause fluctuations in the rate of increase in fruit volume and deviations from linearity, whereas the fruit load affects the slope of the line (Assaf et al. 1982). Since these measurements are made on selected fruit, the

correspondence between them and the weighted averages of fruit sizes measured at harvest is not always perfect. In 1983 only the fruit of T₄ showed symptoms of water deficit resulting in deviations from linearity and a smaller final volume. This phenomenon was more severe in Golden Delicious than in Jonathan (Figs. 27,28).

In 1984 the fruit of T₄ in Golden Delicious showed a reduced slope of growth rate with small deviations from linearity compared to the rest of the treatments, which is indicative of increased fruit load (Fig. 29; Table 9). In Jonathan no difference in growth rate between T₁ and T₄ was apparent, and both were lower than in rest of the treatments. Both T₁ and T₄ seemed to be affected by water deficit at the beginning of the season (Fig. 30). In 1985 no difference in fruit growth was apparent between T₁ and T₄ in Golden Delicious, and both seemed to be affected by water deficits at the beginning of the season (Fig. 31). T₆, in which irrigation controlled by heat dissipation sensors at a low SMP was being operated for the first time, showed a severe water deficit from mid-July onwards (Figs. 31,32). No substantial differences in the mineral contents of the leaves and fruit were found between the various treatments either in 1983 or in 1984. For this reason the average results of all treatments are presented in Figures 33 and 34.

The changes in mineral content of the leaves and fruit during the season were similar in both years with few exceptions. The patterns of seasonal changes were similar, and were typical of both the cultivars as found in other recent experiments performed in Upper Galilee under conditions giving high fruit yields (Levin et al. 1981).

DESCRIPTION OF COOPERATION

Dr. Phene visited Israel twice in 1982 and in 1983 for calibrating the sensor and instruct on system design. Dr. Assaf visited Dr. Phene in 1984 for training and learning the operation of the system.

Main achievements of the research

- 1) An automated irrigation system consisting of SMP sensors and a computer were successfully operated in a high yielding apple orchard for three years. To the best of our knowledge, no information has been published on similar studies in fruit trees.
- 2) Signals from four sensors per treatment were averaged and were used as threshold values of two SMP levels for on and off operation of a computerized system of controlled irrigation.
- 3) A complete recording of the on and off times, amount of water, SMP readings of each individual sensor and their average enabled a detailed analysis of the data to be carried out.
- 4) Neutron probe measurements showed differences between the treatments with respect to the irrigated soil volume and the water uptake from different soil layers. The measurements showed that water percolation down to soil layers below the root zone was minimized. This irrigation system thus provided a means for approaching the target of irrigating at the rate of consumptive use at two levels of SMP.
- 5) The response of the trees to treatments at two levels of SMP satisfied our expectations in the following aspects: a) Significantly lower water consumption was obtained at lower SMP level. b) Treatment at the lower SMP level resulted in a reduced wetted volume of soil and consequently a reduced root volume. c) Vegetative growth and yield were significantly lower in the low SMP treatment. Nevertheless fruit size did not differ between the treatments in the third year, after two years of smaller fruit size. This probably reflected an adjustment process.
- 6) The fruit load, expressed as yield per unit trunk area, increment was increased in Golden Delicious and remained unchanged in Jonathan at the end of the three -year experimental period. These results show that restricting

the root system by controlled irrigation under field conditions reduced vegetative growth without reducing productivity (i.e the ratio of reproductive to vegetative growth was increased). It is expected that this technique of irrigation will allow more trees to be planted per hectare, reduce agrotechnical operation costs, improve light penetrations into the canopy and consequently improve fruit quality and possibly even bud fertility. Such a technique might be able to replace the use of dwarfing root-stocks.

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Table 1 Available N-NO₃, P, K (ppm) content of the soil 0-60 cm profile at different distances from the emitter at two dates in each of the years 1983, 1984, 1985 (averages for all treatments)

Date of sampling	Distance (cm)	N-NO ₃ (ppm)	P (ppm)	K (ppm)	Date of sampling	Distance (cm)	N-NO ₃ (ppm)	P (ppm)	K (ppm)
April 1983	25	14.6	13.9	11.8	November 1983	35	18.8	25.2	14.4
						70	19.6	22.1	6.0
April 1984	30	10.0	5.6	11.6	October 1984	30	38.0	21.0	14.4
	70	10.6	4.1	4.8		60	20.4	8.8	8.7
	100	8.1	3.3	4.2		90	15.3	6.3	4.3
May 1985					November 1985	35	13.6	11.8	11.4
	60	16.2	6.5	6.5		70	25.6	7.9	4.9
	100	10.8	5.8	4.6		105	19.4	7.8	3.4

Table 2. Treatment details and total water applied (mm)

Treatments	Application made and SMP threshold			Total water amount (mm)		
	1983	1984	1985	1983	1984	1985
T 1	Electr. ^x -10 kPa	Electr. ^x -5 kPa	Electr. ^x -10 kPa	741	725	722
T 2	Pan evap. coeff. 100%	Pan evap. coeff. 100%	Heat dissipation sensors-10 kPa	866	911	742
T 3	Pan evap. coeff. 100%	Pan evap. coeff. 100%	Neutron probe	889	908	692
T 4	Electr. ^x -25 kPa	Electr. ^x -15 kPa	Electr. ^x -15 kPa	638	689	617
T 5	Pan evap. coeff. 75% ^{xx}	Neutron probe	Pan evap. coeff. 100%	735	849	786
T 6	Pan evap. coeff. 75% ^x ^x	Pan evap. 80% ^{xx}	Heat dissipation sensors-15 kPa	731	809	653

x - electrotensiometers

xx - the lower amounts of water were applied during the main apple growing period - from mid-June to harvest.

All treatments were irrigated by 8 l/h drippers ("Netafim", Israel) spaced 1.5 m apart on a single lateral per row.

Table 3. Water amounts applied (mm) at different growth periods.

Period /	Treatments ₁	2	3	4	5	6
<u>1983</u>						
May 3-June 17	178	167	163	156	174	193
- Sept. -1	417	515	527	356	431	412
- Sept. 29	96	134	149	76	100	96
- Oct. 10	50	50	50	50	30	30
Total	741	866	889	638	735	731
<u>1984</u>						
April 1-June 17	148	190	158	150	160	185
- Aug. 29	325	446	471	288	400	374
- Oct. 8	189	215	215	196	211	184
Oct. 29	63	60	64	55	78	66
Total	725	911	908	689	849	809
<u>1985</u>						
May1-June 13	158	168	182	149	167	162
- Sept. 4	442	455	412	394	511	421
- Oct. 8	122	199	98	74	108	70
Total	722	742	692	617	786	653

Table 4. Effect of irrigation treatments on transpiration, stomatal resistance and leaf temperature, averages for all measurements conducted between June 25 and October 15, 1984.

Treatments	Transpiration ₁ mgH ₂ O.dm ⁻² .h	Leaf stomatal resistance S.cm	Leaf temperature °C
1	5608 a	1.48 cd	33.69 b
2	4837 b	1.68 bc	31.96 b
4	4440 b	2.27 a	35.44 a
5	5784 a	1.40 d	33.67 b
6	5100 ab	1.81 b	33.48 b
F	6.37	14.14	5.24
P	0.0001	0.0001	0.0004

Letter separation at the indicated P values

Table 5. Effect of irrigation treatments on transpiration, stomatal resistance and leaf temperature at various hours during the day (averages for all measurements conducted during the season of 1984)

Treatment	Transpiration $\text{mg dm}^{-2} \text{h}^{-1}$			Stomatal resistance S.Cm^{-1}			Leaf temperature $^{\circ}\text{C}$		
	8 - 10 am	10 - 12 am	after 12 am	8 - 10 am	10 - 12 am	after 12 am	8 - 10 am	10 - 12 am	after 12 am
1	4899	6364 a	5192 ab	1.47	1.34 b	1.85 ab	30.3	35.1 b	36.1
2	4828	5476 a	3911 b	1.57	1.55 b	2.24 a	30.0	34.3 b	34.5
4	5425	3834 b	4710 ab	1.29	2.74 a	2.42 a	30.4	36.8 a	39.1
5	5460	6070 a	5958 a	1.42	1.34 b	1.45 b	32.1	34.3 b	35.3
6	5163	5596 a	4283 b	1.71	1.55 b	2.49 a	32.3	34.5 b	36.2
Average	5121	5606	4976	1.53	1.66	1.98	31.2	35.1	36.2
F	0.70	12.34	4.60	1.61	29.35	6.96	2.54	7.34	4.97
P		0.0001	0.0028		0.0001	0.0001	0.0423	0.0001	0.0017

Letter separation at the indicated P values.

Table 6. Effect of fruit irrigation treatments on transpiration, stomatal resistance and leaf temperature before and after harvest (Sept. 23, 1984).

Treatments	Transpiration mg H ₂ O dm ⁻² h ⁻¹		Leaf resistance S.cm		Leaf temperature °C	
	+ Fruit	- Fruit	+ Fruit	- Fruit	+ Fruit	- Fruit
1	5928 a	5493 a	1,37 b	1,50 c	33,5 a	33,6 b
2	5145 a	4837 a	1,38 b	1,68 bc	30,3 b	32,0 b
4	4440 b	3818 b	2,27 a	2,74 a	35,4 a	37,0 a
5	5978 a	5398 a	1,32 b	1,44 c	33,5 a	33,2 b
6	5641 a	4683 a	1,47 b	1,92 b	33,4 a	32,8 b
Average	5498 A	5012 B	1,55 A	1,722 B	33,40	33,31
F	7,04	6,27	24,30	21,12	7,40	10,80

Significant differences at $P = 0.0001$ by letter separation.

Table 7. Apple yield (t/ha) and number of fruit (no/ha x 10⁵)

		<u>Golden Delicious</u>											
Year	Treatment	1				2				3			
		t/ha	no/ha	t/ha	no/ha	t/ha	no/ha	t/ha	no/ha	t/ha	no/ha	t/ha	no/ha
1983		144	10.12	140	10.13	148	10.60	89	7.27	101	7.38	140	10.13
1984		72	6.47	83	7.04	89	7.54	71	6.44	73	5.99	75	6.21
1985		90	6.95	84	6.35	87	6.80	67	5.25	93	7.16	82	6.35
Average													
1983, 84, 85		102 ^a		102 ^a		108 ^a		76 ^b		89 ^{ab}		99 ^a	
<u>Jonathan</u>													
1983		99	8.10	103	9.03	103	8.74	73	6.92	83	7.50	97	8.41
1984		46	4.36	45	4.34	40	3.81	32	3.28	37	3.23	40	3.80
1985		67	5.85	74	6.50	64	6.08	43	3.90	64	5.40	53	4.64
Average													
1983, 84, 85		71 ^a		74 ^a		69 ^a		49 ^b		61 ^{ab}		63 ^{ab}	

Significant differences by letter separation P = 0.05

Table 8. Fruit size distribution (%) small - less than 6 cm, medium - 6 cm, large - larger than 6 cm / diameter

Treatments	1983			1984			1985					
	small %	medium %	large %	weighted average cm	small %	medium %	large %	weighted average cm				
Golden Delicious												
1	0	2.2	97.8	6.92	1.5	63.0	35.5	6.20	0	19.5	80.5	6.64
2	0	3.9	96.1	6.83	0.4	38.4	60.8	6.38	0	15.7	84.3	6.71
3	0	5.8	94.2	6.87	0.2	42.8	57.0	6.35	0	27.6	72.4	6.63
4	0	29.0	71.0	6.47	1.3	72.6	26.1	6.14	0	25.1	74.9	6.61
5	0	5.2	94.8	6.79	0	30.8	69.2	6.45	0	19.8	80.2	6.67
6	0	7.1	92.9	6.83	0	34.1	65.9	6.34	0	23.0	77.0	6.64
Jonathan												
1	0.5	20.7	78.8	6.65	17.0	33.8	49.2	6.25	7.6	24.7	67.7	6.48
2	3.6	33.8	62.6	6.45	14.8	43.1	42.1	6.20	10.9	22.8	66.3	6.48
3	6.0	23.1	70.9	6.56	12.4	35.6	52.0	6.26	15.3	36.4	48.3	6.27
4	10.8	36.6	52.6	6.22	31.3	31.8	36.9	6.05	12.6	28.1	59.3	6.38
5	9.3	27.5	63.2	6.39	8.7	29.4	61.9	6.46	5.8	20.3	73.9	6.57
6	2.6	28.3	69.1	6.48	18.1	32.3	49.6	6.25	9.4	24.8	65.8	6.47

Table 3 Trunk area increment (cm^2) and fruit load (Kg fruit per cm^2 trunk area increment per tree)

Golden Delicious							
Treatments	1983		1984		1985		1983, 84, 85 Increment fruit load cm ²
	Increment cm ²	fruit load	Increment cm ²	fruit load	Increment cm ²	fruit load	
1	17.2	10.1	11.9	7.3	15.9	6.8	X45.0a 7.60
2	15.1	11.1	14.7	6.8	13.8	7.3	43.6a 7.91
3	19.0	9.4	12.4	8.6	15.6	6.7	47.0a 7.74
4	10.5	10.2	8.7	9.8	9.7	8.3	28.9b 8.89
5	17.3	7.0	12.8	6.9	11.9	9.3	42.0a 7.19
6	15.1	11.1	14.9	6.0	12.0	8.3	42.0a 7.92
Jonathan							
1	15.8	7.6	9.2	6.0	14.6	5.5	39.6a 5.98
2	14.3	8.7	15.5	3.7	11.9	6.7	41.7a 5.97
3	15.8	7.8	13.6	3.6	9.3	8.3	38.7a 5.97
4	11.9	7.4	6.0	6.3	12.8	4.0	30.7b 5.37
5	15.0	6.7	14.6	3.0	16.0	4.8	45.6a 4.52
6	14.7	8.0	13.6	3.5	10.4	6.1	38.7a 5.45

x. Significant differences by letter separation P = 0.05

Fig. 1. Soil Water Retention Curve

Fig. 2. Hydraulic Conductivity vs. Soil Water Content.

Fig. 3. Sensor Operation Chart.

Fig. 4. Diurnal SMP in T1 1983

Fig. 5. Diurnal SMP in T4 1983

Fig. 6. Diurnal SMP in T1 1984 and calculated theoretical line

Fig. 7. Diurnal SMF in T4 1985 and calculated theoretical line

-x Pa

↓ open=
|| close

Hours of the day

Fig. 8. Diurnal SMP in T1 1985

Fig. 9. Diurnal SMP in T4 1985

Fig. 10. Diurnal SMP in T2 and T6 1985.

Fig. 11. Class A pan evaporation.

Fig. 12. Seasonal changes of volumetric soil water content (%) of T1 in 1983 at three soil layers and two distances (cm) from the emitter.

Fig. 13. Seasonal changes of volumetric soil water content (%) of T3 in 1983 at three soil layers and two distances (cm) from the emitter.

Fig. 14. Seasonal changes of volumetric soil water content (%) of T4 in 1983 at three soil layers and two distances (cm) from the emitter.

Fig. 15. Seasonal changes of volumetric soil water content (%) of T6 in 1983 at three soil layers and two distances (cm) from the emitter.

Fig. 16. Seasonal changes of volumetric soil water content (%) of four treatments in 1983 at two soil layers and 35 cm distance from the emitter.

Fig. 17. Seasonal changes of volumetric soil water content (%) of four treatments in 1983 at two soil layers and 75 cm distance from the emitter.

Fig. 18. Seasonal changes of volumetric soil water content (%) of T1, in 1984 at three soil layers and three distances (cm) from the emitter.

Fig. 19. Seasonal changes of volumetric soil water content (%) of T2 in

Fig. 20. Seasonal changes of volumetric soil water content (%) of T3 in 1984 at three soil layers and two distances (cm) from the emitter.

Fig. 21. Seasonal changes of volumetric soil water content (%) of T4 in 1984 at three soil layers and three distances (cm) from the emitter.

Fig. 22. Seasonal changes of volumetric soil water content (%) of T5 in 1984 at three soil layers and two distances (cm) from the emitter.

Fig. 23. Seasonal changes of volumetric soil water content (%) of T6 in 1984 at three soil layers and two distances (cm) from the emitter.

Fig. 24. Seasonal changes of volumetric soil water content (%) of T1 and T4

at 100% soil moisture and two distances (cm) from the emitter

Fig. 25. Seasonal changes of volumetric soil water content (%) of T2 and T6 in 1985 at three soil layers and two distances (cm) from the emitter.

Fig. 26. Seasonal changes of volumetric soil water content (%) of T3 and T5 in 1985 at three soil layers and two distances (cm) from the emitter.

Fig. 27. Seasonal fruit volume growth of cv. Golden Delicious in 1983.

Fig. 28. Seasonal fruit volume growth of cv. Jonathan in 1983.

Fig. 29. Seasonal fruit volume growth of cv. Golden Delicious in 1984.

Fig. 30. Seasonal fruit volume growth of cv. Jonathan in 1984.

Fig. 31. Seasonal fruit volume growth of cv. Golden Delicious in 1985.

Fig. 32. Seasonal fruit volume growth of cv. Jonathan in 1985.

Fig. 33. Seasonal changes in leaf mineral content (% of dry matter) in 1983 and 1984 in cvs. Golden Delicious and Jonathan.

Fig. 34. Seasonal changes in mineral content (% of dry matter) of whole apples in 1983 and 1984 in Golden Delicious (G.D.) and Jonathan (J).

BARD Research Project No. I-274-80

TITLE: OPTIMIZATION OF WATER AND NITROGEN APPLICATION BY AUTOMATED
 DRIP IRRIGATION CONTROL FOR APPLE TREES

Cooperator's Report - C. J. Phene

TITLE: Optimization of Water and Nitrogen Application by Automated Drip
Irrigation Control for Apple Trees

Cooperator's Report - C.J. Phene

Cooperation specified on page 50 of project outline states that the US Cooperator's responsibility is to develop an irrigation control system for field crops and to advise the Israeli investigators in installing, operating, and adapting the system for fruit trees. The cooperator is to cooperate in all phases of operations, measurements and interpretation of results.

I. Development of US Irrigation Control System

Several experiments have been conducted using the original electronic soil matric potential sensor in the field and laboratory by Phene et al. (1973); Phene and Beale (1976), and Phene et al. (1979) to demonstrate the validity of the concept of high-frequency irrigation control under extreme dynamic conditions. Shallow, layered sandy loam soils and potentially high rainfall had to be accounted for by the automatic irrigation scheduling system to prevent long periods of low aeration caused by water saturated soil. The control system satisfied the variable crop water requirement conditions as affected by rapidly changing external parameters (climate and soil) and the localized application of water by a drip system buried in the rootzone caused the soil between the beds to dry and provide storage for rainfall events of up to 2 cm (Phene and Beale, 1976).

The commercial electronic soil matric potential sensors were tested as input devices for an irrigation controller to schedule irrigation in several replicated experiments (Phene et al, 1981). The field plots were planted to processing tomatoes (*Lycopersicon esculentum* Mill, UC82B) and irrigated at three soil matric potential thresholds by subsurface trickle irrigation. Results demonstrated that high-frequency trickle irrigation can be controlled accurately by soil matric potential sensors in the root zone of row crops. Yields of processing tomatoes obtained by this irrigation scheduling method were comparable to yields obtained with irrigation scheduling based on calculated evapotranspiration. The sensors can be used in a feedback mode to maintain a portion of the root zone at nearly constant Ψ_m within an optimal Ψ_m range (Phene et al. 1984).

The electronic soil matric potential sensors were used as input devices for an irrigation controller to schedule irrigation in three treatments of a replicated experiment (randomized block design). Fig. 1 shows the flow diagram of the software systems used to control the irrigation system with a microcomputer controller. One sensor was measured hourly in each of three replicated trickle irrigation plots to provide an average soil matric potential treatment. The sensors were installed at 45 cm depth midway between two emitters (emitters were spaced 60 cm apart) and 15 cm from the trickle line. In 1981, the soil matric potential sensors were used to initiate a 30-min irrigation (1.2 mm per irrigation) when the mean soil matric potential reached -15, -25, and -35 J/kg early in the season (Treatments T6, T7, and T8, respectively) and later the thresholds were readjusted to lower

Fig. 1. Flow chart showing the logic system for the irrigation controller.

values of -25, -35, and -45 J/kg and finally to -30, -45, and -55 J/kg before harvest. In 1982, the initial threshold value for T6 was lowered to -20 J/kg to minimize excessive irrigation early in the season. The setting of the optimal Ψ_t (desired Ψ_m for initiating irrigation) is based on the average soil characteristics, as defined by Phene and Beale, (1976) and the soil water desorption curve.

The performance of the irrigation controller is related to four basic factors: (a) the adequate operation of the systems's hardware, such as scanning and measuring instrumentation, interfaces to the computer, the computer and the printer; (b) the proper algorithm for the system's software (computer program); (c) the adequate operation of the input instrumentation, in this case, the soil matric potential sensors installed in the field and (d) the adequate operation of the system's output, the solenoid valves, the pressure regulators, flowmeters and filters which are used to distribute the water to the field. Results from above and subsequent experiments have demonstrated the validity of the concept and that the performance of the irrigation controller, as defined by the four factors above, was satisfactory (Phene et al, 1981; Phene and Howell, 1984; and Phene, 1985).

Fig. 2. Soil matric potential fluctuations at 45 cm depth, measured in 1982 by soil matric potential sensors #4, 5, and 6 for constant threshold (Ψ_t) of -20 J/kg and irrigation system controlled by the calculated mean of the 3 sensors.

Fig. 2. shows the responses of three soil matric potential sensors to rapid soil matric potential changes in three plots irrigated simultaneously as a treatment by high-frequency subsurface trickle irrigation. Hourly, the computer calculates the average of the measurements of the three soil matric potential sensors, then compares the average soil matric potential to the threshold (Ψ_t) to determine the need for irrigation to maintain the desired constant soil matric potential threshold (Ψ_t), in this case, -20 J/kg. The number of irrigations per day, shown for each day above the x-axis, varied between 5 and 15 per day during the seven day period. There were 168 individual sensor measurements made in each of these plots by sensors 4, 5, and 6. The mean of 504 measurements made in the three plots was -20.0 J/kg. Similarly, the means, standard deviations and ranges of each sensor were -23.2 ± 0.8 and 3.7; -14.6 ± 0.1 and 2.1; and -22.1 ± 0.4 and 2.3 J/kg, respectively for sensors 4, 5, and 6.

Fig. 3. Soil matric potential fluctuations at 45 cm depth, measured by a soil matric potential sensor during a drying period following the 1982 experiment (no irrigation or rainfall).

Fig. 3 shows the diurnal soil matric potential fluctuations at 45 cm depth during a soil drying period (no irrigation or rainfall) after harvest time. During that period the soil matric potential decreased from -82 to -165 J/kg with diurnal variations of 50 J/Kg. The sensor responded quickly to soil water extraction during the period of peak water use (10:00-16:00 h) with practically no substantial time lag as indicated by the peaks. In all three days, the soil matric potential quickly started recovery after 18:00 h, however, the sensor seemed to plateau -82 J/kg at 4:00 h on day 196, at -115 J/kg at 6:00 on day 197 but it did not plateau on day 198. These data demonstrate the capability of the sensor to measure rapidly changing soil matric potential in a range which is critical to soil water and irrigation research.

The cooperator made two visits to Israel, the first in 1982 and the second in 1984. During these visits, the greatest amount of time was spent at the Motorola-Israel facilities to help design, build, and operate the control system with a Motorola Computer-Data Acquisition system. Because of the difference in computer input/output architecture, the task was difficult and the system never worked to full satisfaction except maybe for a brief period in 1985. It is suggested that in future cooperative experiments of this kind, the system should be developed using the hardware which will be used for the experiment, as was done in the US with Hewlett-Packard equipment.

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