

**TRANSPIRATION RATE AND WATER STATUS OF A MATURE AVOCADO ORCHARD AS
RELATED TO WETTED SOIL VOLUME**

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A mis padres Raúl y Cora y a mi hermano Raúl por darme la oportunidad, la fuerza y el apoyo, y a Dios por haberme permitido cumplir esta tarea.

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ABBREVIATIONS AND SYMBOLS

<u>Variable</u>	<u>Symbol</u>	<u>Units</u>
Air temperature	T _a	°C
Canopy temperature	T _c	°C
Canopy temperature measured with a hand-held infrared thermometer	T _{c_{man}}	°C
Canopy temperature measured with a fixed-position infrared thermometer	T _{c_{stat}}	°C
Coefficient of Determination	R ²	
Evapotranspiration	ET	mm day ⁻¹
Latent heat flux	E	W m ⁻²
Leaf Area Index	LAI	
Leaf Water Potential	LWP	MPa
Modeled transpiration, according to Avissar et al. (1986)	T*	l day ⁻¹
Net radiation	R _n	W m ⁻²
Potential transpiration, according to Fuchs et al. (1987)	T _p	mm day ⁻¹
Pre-dawn leaf water potential	PLWP	MPa
Ratio between measured to potential transpiration	T/T _p	
Sensible heat flux	H	W m ⁻²
Sodium Absorption Ratio	SAR	
Soil (conductive) heat flux	S	W m ⁻²
Soil temperature	T _s	
Transpiration rate	T	mm day ⁻¹ or l day ⁻¹
Vapor pressure deficit	VPD	MPa

I. GENERAL INTRODUCTION.

1.1. Description of the problem

The avocado crop in Israel has expanded rapidly in the last 30 years, now accounting for approximately 12,000 ha, with average national yields ranging between 9 and 13 tonne ha⁻¹ (Lomas, 1992). Most of the commercial orchards are concentrated in the central coastal plain, where the climatic conditions satisfactorily meet the crop requirements.

The avocado's importance in the Israeli fruit industry has increased, due to the increase in exports: almost twofold, from 1988 to 1992. In 1992 the avocado fruit export, mainly to the European market, reached 52.5 thousand tons, comprising 4.5% of the total fruit exports of the country, third in importance after citrus and apples (Affleck, 1992; FAO, 1992). However, the commercial production of avocado in Israel is restricted by large variations of yield among years that may reach 40-60% depending on the cultivar, climatic and site-specific factors (Lomas, 1992). This significant yield variability produces large fluctuations of export volumes between years, that cause serious marketing problems and economic losses to avocado growers in Israel. Therefore, information relating to proper crop management becomes increasingly important.

Several studies have been carried out in order to determine the factors affecting avocado yield in Israel. Among the main factors that have been described as directly affecting the avocado yield, considerable emphasis has been placed to the climate, the irrigation regime and the factors affecting the process of water uptake from the soil by the roots (Kalmar and Lahav, 1977; Lahav and Kalmar, 1977; Lahav and Trochoulis, 1981; Lahav and Kalmar, 1982; Levinson and Adato, 1991; Lomas, 1988; Lomas, 1992; Lomas and Zamet, 1994; Michelakis et al., 1993; Natan et al., 1991; Scholefield et al., 1980; Schroeder, 1976; Sedgley, 1977; Sedgley and Annells, 1981; Shilo, 1986; Steinhardt and Tomer, 1988; Steinhardt et al., 1989; Sterne et al., 1977; Whiley et al., 1988b).

Climatic factors influencing the evaporative atmospheric demand are responsible for variations in water use during the growing season. The influence of adverse temperatures occurring during the critical stages of flowering and fruit set, has been pointed out as one of the main factors responsible for the low fertility and yield variations observed in avocado orchards in Israel. Conditions of high temperatures accompanied by low relative humidity during the spring season cause a massive abscission of fruits and leaves in avocado, reducing the canopy evaporative area and the potential fruit yield (Argaman, 1983; Gafni, 1984; Levin, 1981; Lomas, 1988; Lomas, 1992; Tomer, 1977). It is well known that at times of high evaporative demand, water stress develops in the canopy of avocado trees, as a consequence of an excessive transpiration rate over the rate of uptake and conduction of

water from the soil. If soil water stress develops at the first stages of fruit set, a strong competition for water will develop between the fruits and the leaves. As a result of such competition, the leaves extract water from the young avocado fruits, which shrink very severely and drop (Lahav and Kalmar, 1982). Tree physiological responses to such environmental conditions determine the adaptation and performance of irrigated avocado trees growing in semi-arid environments (Scholefield et al., 1980).

Among the principal management factors influencing avocado yield, the irrigation regime has been extensively studied under various soil and weather conditions in the main cultivated areas in Israel (Kalmar and Lahav, 1977; Lahav and Kalmar, 1977; Lahav and Trochoulis, 1981; Lahav and Kalmar, 1982; Natan et al., 1991; Steinhardt and Tomer, 1988; Steinhardt et al., 1989). The effect of adequate irrigation is determinant during the periods of heat load occurring in the flowering and fruit set stages in order to avoid canopy water stress. Irrigation strengthens and accelerates the natural ability of the trees to adapt to harsh conditions (Levinson and Adato, 1991).

The maintenance of a tree water status adequate for achieving maximal yield depends on the ability of the avocado root system to take up the required available water from the soil. Avocado roots may supply enough water to satisfy tree requirements, as long as their activity is not limited by external or internal factors (Borys, 1986; Gefen, 1981; Lahav and Trochoulis, 1981; Lomas and Zamet, 1994). However, under high evaporative demand conditions like those occurring in the spring season in Israel, even the water supplied by irrigation is not enough to prevent canopy water stress and fruit drop (Honing and Lavee, 1989). This fact has been attributed to a limited size of the root system in the early spring season (Gefen, 1981).

The spatial distribution of avocado roots is affected by the pattern of soil moisture and soil hydraulic conductivity (Atkinson, 1980). One method for increasing the supply of water available to the tree is through increasing the total soil volume occupied by the roots (Taylor et al., 1983). Previous studies have demonstrated that avocado root distribution closely follows the wetted soil volume (Levinson and Adato, 1991; Michelakis et al., 1993), but it is not clear whether enlarged wetted soil volume increases root-mass production and water uptake capability of the total root system, as compared with a limited wetted soil volume. Therefore, we tested the effect of enlargement of the wetted soil volume on root growth, water uptake and canopy water status of an adult avocado orchard, during periods of high atmospheric evaporative demands in the flowering and fruit set stages. Measurements of leaf water potential, canopy temperature and tree transpiration were utilized to monitor the effect of enlargement of the wetted soil volume on avocado canopy water status.

1.2. Hypothesis and Objectives

In our study we considered two factors influencing the avocado water status: (i) the effect of wetted soil volume on the capacity of the tree to take up water from the soil in order to maintain an adequate canopy water status, and (ii) the effect of severe climatic conditions on tree water status during critical growth stages.

The main hypothesis associated with the experiment was that the development of a more extensive root system by enlargement of wetted soil volume via irrigation will improve the water uptake from the soil, and will therefore prevent deterioration of the tree water status during periods of environmental stress. Determination of a threshold value of available water required in the active root zone to maintain an adequate water status of the avocado tree will facilitate the control of irrigation for a minimum water stress risk.

Flowering is a major event in the growth cycle of avocado. In Israel, conditions of environmental stress during the flowering season are associated with considerable yield loss in commercial orchards. Consequently, the secondary objective of this study was to determine the effect of high evaporative demands occurring during the flowering and fruit set period on avocado tree water status and yield potential.

II. LITERATURE REVIEW.

2.1. Plant water status

As Kramer (1962) stated, internal water deficits can be the result of excessive transpiration or of slow water absorption from dry, cold or poorly aerated soil or, more commonly, a combination of both. Transpiration and absorption, which are partially controlled by different sets of factors, are usually out of phase. Transpiration is largely controlled by the aerial environment (solar radiation, temperature, humidity, wind, etc.) as well as by leaf structure and stomatal opening. Absorption is controlled by the rate of transpiration, but it is also regulated by the size and distribution of the root system and several soil factors (temperature, soil moisture, aeration, osmotic potential). Recurrent temporary wilting of leaves at times when transpiration exceeds absorption is not serious in well-watered soils, because leaves usually recover turgidity at night. However, wilting becomes serious when soils begin to dry out, because leaves are less likely to recover turgidity at night.

Regular diurnal development of internal water stresses in plants is shown by a decrease in leaf conductance, photosynthesis rate and tissue water potential, as well as by increased leaf temperature and plant resistance to water flow. In a study conducted on an 8-year-old avocado orchard established on a sandy loam soil in California, Sterne et al. (1977) found a clear dependence of leaf xylem water potential on the transpiration rate of unstressed trees. Leaf conductance and transpiration were higher in well-watered trees than in stressed trees. On the contrary, in water-stressed avocado trees a severe reduction of the xylem water potential and leaf conductance has been observed (Scholefield et al., 1980).

Canopy water status is determined by soil water potential. Variations of soil water potential influence the diurnal pattern of water relations in several tree species. Hilgeman et al. (1969) showed that under the same atmospheric conditions, "dry" citrus trees (soil water potential -76 kPa) had lower transpiration rates than "wet" citrus trees (soil water potential 29 kPa) throughout the day. Lombard et al. (1965) found that soil potential did not influence fruit and leaf growth of citrus trees until it had fallen from 20 kPa to -100 kPa. They considered that the large associated decline in soil capillary conductivity (from 15×10^{-4} to 0.5×10^{-4} cm h⁻¹) exerted considerable influence on growth of these organs. The effect of soil water depletion on tree water status has also been reported for avocado trees. Sterne et al. (1977) observed that in avocado trees stressed by withholding water for 30 days, there was no longer a consistent relationship between xylem water potential and transpiration of leaves, as in non-stressed trees. The progressive reduction in soil matric potential lead to a sharp decrease of soil hydraulic conductivity, thus reducing water flow to the roots. This decrease in hydraulic conductivity and increased root

resistance in the dry soil might explain why xylem water potential in stressed avocado leaves was uncoupled from transpiration.

2.2. Factors determining avocado tree water status

The avocado is a perennial evergreen tree indigenous to the rain forests of the humid subtropical and tropical highlands of Central America. Its subtropical origin explains its high sensitivity to heat radiation and moisture stress (Wolstenholme, 1977), although the general success of commercial avocado crops over a wide range of environmental conditions suggests some degree of morphological, anatomical and/or physiological adaptation of the tree to water stress (Whiley et al., 1988b). The study of avocado water status and its response to environmental conditions during the different growth stages will contribute to reducing the potential risk of yield loss and to improving irrigation management of commercial orchards.

Plant water status depends on the balance between the soil water taken up by the root system and the water requirement imposed by the evaporative demand. It is well known that at times of high evaporative demand, water stress develops in the canopy of avocado trees, as a consequence of an excess of transpiration over uptake and conduction of water from the soil (Lahav and Kalmar, 1982). Under the daily stress conditions the water needed by the tree can be partially supplied by the water stored in its tissues. Schroeder and Wieland (1956) showed that avocado fruits and roots function as water reservoirs and they shrink at times of intensive transpiration. However, severe water stress at the first stages of fruit set will result in a strong competition for water between the fruits and the leaves. As a result of such competition, the leaves extract water from the young avocado fruits, which shrink very severely and if they do not regain their turgidity, abortion will eventually take place (Borys, 1986). High transpiration rate and low soil water content promote fruit drop in avocado (Borys et al., 1985).

Irrigation is probably the most important agronomic management factor in controlling tree water status. The soil wetting pattern determines the growth response of the root system, thus affecting the water uptake capacity of the tree. Well-watered trees are able to increase their transpiration rate when high evaporative demand conditions occur, thus preventing water stress in the canopy. The irrigation systems generally used in avocado orchards in Israel are either drip or mini-sprinkler, in which the wetted soil volume is limited to about 25-50% of the total soil volume. The rest of the soil is left under the cycle of wetting during the winter and drying during the rest of the year. The effect of these wetting and drying cycles on tree water status is not clear.

The availability of water is related to the soil hydraulic conductivity and soil water content, but also depends strongly on the density and depth of the rooting system of plants. The total quantity of water available increases

both with soil water content and with the volume occupied by roots (Cowan 1965; Gardner, 1960; Taylor et al., 1983). One strategy for increasing the soil volume occupied by the roots is to increase root extension rate, by modifying biological, chemical and physical soil factors that affect root elongation and thus the soil volume explored by roots. Irrigation is one of the most effective management factors in affecting root growth. Taylor and Klepper (1978) observed that large changes in crop root density are possible during a very short time interval if the water regime is altered. Feddes (1971) demonstrated that the root density-depth relationship changes as the water content of the root zone is depleted, and that the zone of effective uptake is not necessarily the same as the spatial extent of the actual root zone. In a study of the effect of trickle irrigation on apple root growth in Israel, Levin et al. (1973) found that root distribution depended upon the volume of wetted soil, which was related to soil hydraulic conductivity and the rate and duration of water application. The wetted soil volume was usually 30-50% of the whole. The root system adapted to this by becoming restricted to within 60 cm of the emitters.

The response of the avocado root system to irrigation demonstrates that root distribution closely follows the wetted soil volume (Levinson and Adato, 1991; Michelakis et al., 1993), but it is not clear whether an enlarged wetted soil volume increases root growth and hence the water uptake capability of the total root system, as compared with a limited wetted soil volume.

2.2.1. Root growth

The capacity of an avocado tree to take up water from the soil in order to satisfy the evaporative demand is determined by the root system characteristics. The avocado has a highly branched and highly suberized root system, with a low hydraulic conductivity and low growth rate of root hairs (Possingham and Kriedeman, 1986). The genetic factors of both the rootstock and the scion seem to be involved in avocado root spread and some root-size components (Borys et al., 1985). Several studies have established that water is taken up from the upper soil layers, where most of the avocado roots are concentrated (Gutafson et al., 1979; Kalmar and Lahav, 1977; Levinson and Adato, 1991). In a study conducted on one-drip-line irrigated avocado trees in Greece, Michelakis et al. (1993) found that 72% of the root system was concentrated in the upper 0.5-m soil layer and within 2 m on either side of the drip line.

The periodicity of root growth has been studied on field-grown avocado trees. Whiley and co-workers (1988a) reported a general growth model for shoots and roots of avocados. Root growth was described as a clear two-peak curve, with maximum root activity registered in the early summer and mid-autumn respectively. Root growth of avocado trees is cyclic because of a consistent alternation with periods of shoot growth (Ploetz et al.,

1993). This pattern of growth is consistent with the concept of an inherent competition between roots and shoots for available assimilates.

A limited root activity during the early spring months, due to a reduced water uptake capacity, has been associated with the development of water stress in avocado trees during periods of high evaporative demands (Gefen, 1981; Lahav and Kalmar, 1982). Under these conditions, even the water supplied by irrigation was not enough to prevent canopy water stress and fruit drop (Honing and Lavee, 1989).

The annual pattern of root growth in tree crops varies with species and is closely related to environmental factors, particularly soil temperature and soil water content (Bevington and Castle, 1985; Taylor et al., 1983). Soil temperature variation both with depth and time of year under field conditions is likely to influence the relative activity of roots at different depths in the soil and within a season (Atkinson, 1980). The relationship of soil temperature to avocado root growth has been analyzed in previous studies (Lahav and Trochoulis, 1981; Ploetz et al., 1993; Yousof et al., 1969). Day/night soil temperature ranges of 21.5/14.0°C to 25.2/18.0°C measured at 0.30 m depth were reported by Lahav and Trochoulis (1981) as the optimum range for root growth of avocado seedlings. Whiley et al. (1988a) concluded that avocado rate of root growth is dependent of soil temperature, with significant root growth starting in the early spring season when the soil temperature increases above 18°C in the active root zone. Soil temperatures higher than 30°C have been reported as detrimental for avocado root growth (Lahav and Trochoulis, 1981; Yousof et al., 1969). Lomas and Zamet (1994) found a significant high correlation between soil temperature measured at 0.30 m depth in March and avocado yield, based on data collected over a period of 36 years from avocado plantations in the central coastal plain of Israel. The significant correlation obtained between soil temperature in March and yield is most likely related to the positive effect of increasing soil temperatures on early root activity.

When soil temperature is not limiting, root growth is often highly correlated with the amount of available soil moisture. Limited soil moisture shortens the period of root elongation in trees (Zhaner, 1968). Soil drying mainly affects the growth of tree roots in the upper soil layers, where the highest root concentrations are found. Rapid soil drying, as a consequence of a low irrigation frequency and a high transpiration rate, has been associated with a slower root growth (Atkinson, 1980).

The need for more information on the development and distribution of tree roots in different soils under various ecological conditions has led to the development of several techniques for studying root systems in field trials. The profile wall method has been used by a number of investigators to study the variation of avocado root distribution in response to different irrigation treatments (Gutafson et al., 1979; Levinson and Adato, 1991;

Michelakis et al., 1993). With this method, trenches are dug in the soil and the relative distribution of roots is determined by counting the tips exposed on the profile walls. It is a very suitable method of determining root distribution in the profile.

2.2.2. Effect of severe climatic conditions on avocado water status

Climatic factors influencing the atmospheric demand level are responsible for variations in the tree's water use during the growing season. The major climatic influence on the avocado water requirement in Israel occurs during the flowering process, when conditions of high temperatures accompanied by low relative humidity during the spring season cause a massive abscission of fruits and leaves, reducing the canopy evaporative surface and causing large yield reductions (Argaman, 1983; Gafni, 1984; Lomas, 1988; Lomas, 1992; Lomas and Zamet, 1994; Tomer and Gazit, 1979). Tree physiological responses to such environmental conditions determine the adaptation and performance of irrigated avocado trees growing in semi-arid environments (Scholefield et al., 1980).

The early stages of avocado fruit set are extremely sensitive to high temperatures. Sedgley and Annells (1981) reported that air temperatures of 35°C during the day caused an early and complete drop of fruitlets up to 10 days after fertilization. Other authors have suggested that high temperatures during the avocado flowering and fruit set period are responsible for lower viability of mature pollen (Gafni, 1984), embryo abortion and low yields (Bergh, 1976; Papademetriou, 1976). It is also assumed that, in addition to physiological control mechanisms, air temperature fluctuations are responsible for most of the variability in yield of avocados (Lomas, 1988).

The predisposition of avocado trees to heat stress in a well-managed and irrigated plantation may be affected by many factors. Changes in timing and duration of exposure of the sensitive reproductive organs to heat stress will determine the level of potential reduction of fruit yield. Whiley et al. (1988b) found that avocado floral structures contribute significantly to water loss through epidermal surfaces, thus increasing the canopy surface area and the tree water consumption. This situation can be very critical in environments where conditions of high atmospheric demand are frequent (Blanke and Lovatt, 1993). Based on the increased tree transpiration rates observed during the flowering period, some authors have suggested the need for higher water dosage during this phenological stage (Blanke and Lovatt, 1993; Levinson and Adato, 1991).

Erez et al. (1988) proposed the modification of micro-climatic conditions of avocado orchards by sprinkler irrigation of the canopy during periods of extreme climatic conditions in the flowering stage, thus reducing the probabilities of heat stress damage to reproductive organs. These authors found a reduction of 4°C in the

temperature of fruits that were uniformly and continuously wetted during periods of hot and dry weather, compared with dry fruits. This effect was attributed to an improved evaporative cooling process on the surface of wetted fruits.

2.3. Methods for studying plant water status

Plant water status is the degree to which physiological processes are limited by the availability of water to the plant (Savage et al., 1989). It is usually expressed in terms of water potential, but can also be expressed by relative water content, stomatal resistance, transpiration rate, net photosynthesis rate, leaf temperature or leaf angle. A plant water status index should be chosen to suit the study objectives and the equipment available. The use of a combination of physiological indicators of plant water status would allow a better comprehension of the factors affecting the tree's water relations, and a more accurate quantification of the canopy stress level.

2.3.1. Xylem water potential

Plant water potential is the parameter most commonly measured to evaluate water status, since it is closely related to physiological functions. Thus, a decrease in water potential under given conditions, relative to the water potential of well-watered plants can be correlated with yield and productivity.

Pressure chambers (Scholander et al., 1965) have been used for determining the water potential of leaves, twigs, roots, fruits and tubers. In this method, the excised organ - usually a leaf - is placed in a sealed chamber with only the cut end exposed to the atmosphere, and gas is introduced into the chamber under pressure. The xylem fluid of the organ is forced back to the surface of the cut, which it reaches when the applied pressure exactly balances the xylem water potential at the time of excision.

The time of day for these measurements becomes particularly important, with the lowest water potentials occurring around noon, when the evaporative demand is the highest. Pre-dawn leaf water potential (PLWP) is generally well correlated with relative ET (the ratio of actual to maximum evapotranspiration) and this relationship is independent of soil characteristics and phenological stage. Hence PLWP measurement allows an easy estimate of relative evapotranspiration, which is useful for irrigation scheduling (Cohen, 1995).

2.3.2. Canopy temperature

The measurement of canopy temperature offers another way of assessing the crop water status. This approach is based on the assumption that, when a crop becomes water stressed, stomatal conductance and latent heat exchange are reduced, the cooling effect of evaporation is reduced, and leaves become warmer relative to an unstressed crop. This concept constitutes the basis for the use of canopy temperature measurements for assessing crop water status.

The use of infrared thermometry has become increasingly popular in the last 15 years, since it provides a rapid and accurate procedure for collecting foliage temperature data. With the development of inexpensive infrared thermometers able to measure emitted thermal radiation to an accuracy of about 0.1°C, canopy temperature has become an easily measured parameter. However, meteorological factors such as radiation, air temperature, humidity and wind speed modify leaf temperature and may mask indications of water stress. The position, inclination and orientation of leaves within the canopy also produce considerable variation of leaf temperature. Fuchs (1991) demonstrated that the temperature-averaging process that occurs in the field of view of infrared thermometers limits the ability of these instruments to detect moderate stress level above which crop productivity is reduced. Sensitivity is improved when sighting is parallel to incident sun rays.

Canopy temperature measured with infrared thermometers at a fixed point in the tree canopy have the main limitation of not representing actual temperature of the whole canopy (Wanjura and Upchurch, 1991). To overcome this problem, portable hand-held infrared thermometers have been designed for measurements at different locations in the canopy (Hatfield, 1990).

2.3.3. Transpiration rate

The most immediate way of determining the total water flow through a plant is to measure the amount of water passing through the stem between the root system and the canopy (Percy et al., 1991). A recent development in the use of plant parameters for assessment of water status is the use of sap flow measurement in the stem. The use of heat as a tracer to measure sap flow in plants was first proposed by Huber and his colleagues (Huber, 1932; Huber and Schmidt, 1937). Since then, many thermoelectric methods have been developed to improve the assessment of transpiration from whole plants, both for the study of plant water relationships and to improve irrigation management (Cohen, 1994).

If transpiration rate is determined under non-limited soil water availability, it can be considered as the maximum rate for a given combination of leaf area index and atmospheric evaporative demands. Transpiration is often less than the atmospherically determined potential demand, because the latter exceeds the maximum water

uptake and transport rates possible through the soil-plant-atmosphere continuum (Cohen, 1995). The ratio of actual to potential transpiration (T/T_p) has been utilized as a parameter to assess the response of plant transpiration to varying levels of atmospheric demand (Cohen, 1991; Sakuratani, 1977). The T/T_p ratio is determined by the total canopy resistance of the plant. When water potential in the soil becomes low enough, transport of water to the soil surface (for evaporation) and transport of the water through the plant root to the leaves (for transpiration) cannot proceed at a rate high enough to match the potential transpiration. When this happens, the internal water content of the plant begins to decrease and the plant acts to decrease the water loss, by closing stomata or through other mechanisms, such as leaf wilting, folding or abscission (Jury, 1979). Under these conditions, a reduction in the T/T_p ratio is observed. The T/T_p ratio varies widely for different species under unlimited soil water availability. For corn and cotton, maximum transpiration was measured as about 78 and 86% of the atmospheric demand, respectively; for pine 52% and for citrus only 31% (Cohen, 1991; Cohen, 1992).

2.3.4. Soil water status

In order to characterize availability of soil water to plants, four principal parameters may be utilized: (i) soil water content, (ii) water potential, (iii) capillary conductivity, and (iv) soil water diffusivity (Gardner, 1968). Methods for the measurement of all of these have been the object of much research in soil physics.

The gravimetric determination of water content by weighing soil samples before and after oven drying at 105°C is taken as the standard and is used to calibrate all laboratory and field methods of water content measurement. For large-scale field experiments the neutron soil moisture meter has proven to be very useful. In this method a source of fast neutrons is lowered down an access tube into the soil. The fast neutrons are slowed down by collision with nuclei in the soil, particularly those of hydrogen atoms. The flux of these slow neutrons is detected by a scintillation counter mounted just above the fast neutron source. Since water is the main reservoir of hydrogen atoms in the soil, the scintillation count is directly proportional to the soil water content. Other reservoirs of hydrogen atoms are clay lattices and soil organic matter. Large amounts of cadmium, chloride and boron absorb neutrons, but otherwise the neutron soil moisture meter is unaffected by temperature, salinity and pressure. Since soil bulk density influences attenuation of both fast and slow neutrons, the meter needs to be calibrated for each soil type. The advantages of this method are that it is non-destructive and provides the opportunity of repeated

measurements at the same location in the field. The disadvantages are that the sample volume is not accurately known, the calibration is critical and accurate measurement is time consuming (Gardner, 1968; Mottram, 1989).

The tensiometer is the most widely used device for measuring matric potentials greater than -0.08 MPa in the field. This measurement range encompasses the soil water potential range required for most shallow-rooted and quick-growing crops. Proper installation and maintenance of the tensiometers is necessary for accurate measurements. Another method for determining soil water potential involves the use of resistance elements such as gypsum blocks, which are cheap and amenable to automatic datalogging. However, they have limited accuracy, are affected by hysteresis (measurements differ between wetting and drying soils) and are not suitable for saline or acid soils.

Capillary diffusivity and conductivity of soil to the flow of water can be satisfactorily measured by the pressure membrane outflow. This method actually gives the diffusivity from which the conductivity is then calculated.

2.4. Theoretical Background

2.4.1. Determination of tree transpiration based on sap-flow measurement by the heat-pulse technique

Many thermoelectric methods based on the use of heat as a tracer to measure sap flow have been developed in the last 50 years. The heat-pulse velocity method, applied to the measurement of sap flux density, involves measurement of the time elapsed between the release of a heat-pulse into the stem of a plant, and the occurrence of the maximum temperature at various positions at fixed distances up the transpiration stream.

This method has been employed by several workers to obtain accurate estimates of tree transpiration in homogeneous conifers stands and diffuse-porous woody species (Caspari et al., 1993; Cohen et al., 1981; Cohen et al., 1985; Cohen et al., 1987; Cohen, 1991; Cohen, 1992; Green and Clothier, 1988; Miller et al., 1980). The technique has also been utilized for both the study of water transport in trees and investigation of various bioclimatological aspects of canopy water loss in the field. However, the utilization of the heat-pulse technique in the determination of water requirements of avocado trees has not yet been reported. The main advantages of the heat-pulse method are: it is a highly sensitive and accurate technique; it can be automated and is amenable to routine use; and it does not require the measurement of the canopy leaf area to compute the total tree transpiration.

The application of thermal methods for measuring sap flow in trees is relatively simple in practice, but complex theoretically. Sap flow determinations using a heat-pulse as a tracer are based on the solution of the convective heat-diffusion equation. Heat transport in the xylem sapwood of a tree occurs by convection in the flowing sap and by diffusion through the sap and the stationary tissue of both the sapwood and heartwood (Swanson, 1994).

In the original theory, developed by Huber and coworkers (Huber, 1932; Huber and Schmidt, 1937), the heat velocity through the stem was equated to the sap velocity. Marshall's (1958) analysis gave a solid theoretical base to the measurement of xylem sap flow in trees. He showed that, contrary to the opinion of previous workers, the velocity of movement of a heat-pulse through the xylem of a stem was not the same as the sap velocity. He proposed a solution to the convective heat-diffusion equation, with coupled convective transport by sap within an semi-infinite medium. In his analysis, Marshall (1958) considers the tree as a semi-infinite half space, and solves the case of a heat-pulse delivered by a line source inserted radially into the stem, assuming a two-dimensional heat flow. This approach provides a good mathematical description for the heat-pulse obtained from a heating wire radially inserted into a large stem.

In Marshall's equation (Marshall, 1958), the temperature elevation, T , produced by the heat-pulse after time, t , and at a distance $\sqrt{(x^2 + y^2)}$ from the line heater, is given by:

$$T = \frac{H}{4\pi\rho ckt} \exp\left[\frac{-(x-Vt)^2 + y^2}{4ktr}\right] \quad [1]$$

where H is the heat output per unit length of the heater, ρ , c and k are the density, specific heat, and thermal diffusivity, respectively, of wet wood and r is the distance between the line source of heat and the temperature sensor. The heat wave convective velocity, V , is defined as:

$$V = (\rho_1 c_1 / \rho c) J_1 \quad [2]$$

The coefficient of the convective term is $\rho_1 c_1 J_1$, where ρ_1 is the liquid flux density occurring exclusively along the axis of the xylem, x . The density and specific heat of the liquid are designated by ρ_1 and c_1 , respectively. Heat conduction occurs in the wood along the x and y axes in the plane perpendicular to the line heater.

The function defined by equation [1] has a maximum occurring at time t_m , when the first derivative of [1] is equal to zero. This condition yields:

$$V = \sqrt{r^2 - 4kt_m} / t_m \quad [3]$$

For a given value of r , and with known physical and thermal properties of the live wood, the measurement of t_m in equation [3] allows the computation of the water flux J_l in equation [2]. The only property which is difficult to determine is the thermal diffusivity, k of the live wood. Cohen et al. (1981) proposed a simplified approach, in which the value of k is estimated by substitution in equation [3] when V is zero, i.e., no convective transport is taking place. With $V=0$, equation [3] yields:

$$k = r^2 / 4 t_m \quad [4]$$

The temperature wave dissipation at a point below the heater is obtained by replacing (x) with $(-x)$ in equation [1]. If sensors are placed symmetrically above $(+x)$ and below $(-x)$ the heater, the differential temperature wave $T(+x)-T(-x)$ has a maximum occurring at a time t_m which also satisfies equation [3], provided V differs from zero. With V equal to zero, $T(+x)-T(-x)$ is also zero, and its measurement can be used to check the absence of convective transport. This check validates equation [4] and the resulting computation of the thermal diffusivity.

In order to determine the volumetric flow, F , the water flux, J_l , must be integrated over the cross-sectional area of the stem:

$$F = \int_s J_l ds \quad [5]$$

where ds is the element of stem area in which J_l has been determined.

Marshall's (1958) analysis placed the measurement of xylem sap flow on a firm theoretical basis. The use of any equation derived from equation [3] to obtain heat-pulse velocity will result in a value that underestimates the true heat-pulse velocity by 50-75% or more (Marshall, 1958; Swanson and Whitfield, 1981; Swanson, 1994). Marshall's solution considered sapwood in the stem to be comparatively homogeneous. But in most conifers and ring-porous hardwoods, the sap moves up a number of annual rings at different velocities (Kozlowski and Winget, 1963). In addition, underestimation of sap flow by the heat-pulse technique depends upon sensor size, sensor arrangement, sapwood structure, and the reaction of the plant to wounds caused by inserting the sensors into the stem.

The ultimate goal of the measurement of sap velocity is to calculate the sap flow rate. Therefore, the area of active xylem should be determined for every species in order to evaluate the sap flux density. Sampling at several depths into the sapwood is usually necessary to characterize the sap velocity profile. Cohen et al. (1981) proposed a multisensor temperature probe, as an approach to a more accurate characterization of the radial and orientational variability of the sap velocity in the cross-sectional area.

Calibration or verification of the heat-pulse method for every species is necessary as the assumptions used in the heat-pulse theory are related to the structure and function of the water-conducting system in the stem, which varies considerably among species. When all theoretical assumptions are observed in the practical application, the use of the heat-pulse for sap-flow measurement has been proven to be very useful in studies of water transport in trees and investigation of various bioclimatical aspects of canopy water loss in the field.

2.4.2. Micro-meteorological methods for estimating transpiration of an avocado orchard

In the estimation of orchard water requirement, the use of micro-meteorological models for estimating transpiration has widely extended in recent years. In these models, transpiration is estimated by measurements of the vapor gradient above the crop surface, utilizing basic meteorological data as input. Fuchs et al. (1989) developed a transpiration model based on the combined Penman-Monteith equation, which has been adapted to different species by updating data on crop characteristics. Avissar et al. (1986) developed a one-dimensional numerical model which allows the estimation of actual evapotranspiration and total transpiration rate of different crops under various meteorological conditions (Kordova et al., 1993; Kordova, 1995). This model can be used as a guideline for irrigation and as a tool to study the soil-plant-atmosphere interactions in some detail.

2.4.2.1. Potential transpiration calculated by a modified Penman-Monteith model

Potential transpiration (T_p , m s^{-1}) was computed according to a corrected version of the Penman-Monteith combination equation (Fuchs et al., 1987):

$$T_p = [s/(s + \gamma)] Rn] + \{ \rho c_p / \{ (s + \gamma) r_u \} (e_a - e) \} \quad [6]$$

where s is the slope of the saturation vapor pressure curve ($\text{kPa}^\circ\text{C}^{-1}$), γ is the psychrometric constant ($\text{kPa}^\circ\text{C}^{-1}$), Rn is the net radiation flux density at the surface of the sunlit or shaded leaves ($\text{MJ m}^{-2}\text{s}^{-1}$), ρ is the density of air (kg m^{-3}), c_p is the specific heat of air ($\text{MJ kg}^{-1}\text{C}^{-1}$), r_u is the resistance to water vapor transport of sunlit or shaded canopy (s

m^{-1}), and $(e_a - e)$ is the vapor pressure deficit (kPa). Equation 6 expresses the actual evaporative demand of an arid environment. The energy balance in the equation is for leaves, and the conductive heat flux density into the plant and soil can therefore be neglected.

The net radiation, R_n , was computed after Fuchs et al. (1987):

$$R_n = (0.55)^n f K LAI_s - R_{LN} \quad [7]$$

The constant of 0.55 represents the absorption of a single leaf weighted for the mean spectral composition of solar radiation; n is an empirical factor with an assigned constant value of 0.50, which accounts for radiation entrapment resulting from multiple scattering among sunlit leaves; f is the mean horizontal area of the shade cast by leaf unit area; K is the global radiation; LAI_s is the leaf area index of sunlit leaves, and R_{LN} is the net thermal radiation.

The resistance to water vapor transport of the sunlit and shaded canopies, r_u , is computed separately after Thom (1975):

$$r_u = r_A + (r_B / LAI_x) \quad [8]$$

where r_A is the aerodynamic resistance (s m^{-1}), r_B is the boundary layer resistance of a leaf (s m^{-1}), and LAI_x is either the sunlit or the shaded leaf area index.

The aerodynamic resistance, r_A , for the crop is computed after Fuchs et al. (1987):

$$r_A = \{ \ln[(z - D)/z_0] \ln[(z - D)/z_E] \} / k^2 U \quad [9]$$

where $k = 0.41$ is the von Karman constant for turbulent diffusion, U is the wind speed (m s^{-1}) measured at height z (m), D is a displacement height (m) taken as 66% of the average height of the canopy (H), z_0 is the roughness length calculates as $0.05 \times H$ (m), and z_E , the roughness length for sensible heat transfer (m), is 20% of z_0 (Garratt and Hicks, 1973).

The water vapor pathway between the leaf surface and the turbulent atmospheric layer represented by the boundary layer resistance, r_B , was computed after Campbell (1977), assuming that the average lobe of an avocado leaf is 0.1 m in width:

$$r_B = 300(d/U_o)^{0.5} \quad [10]$$

with U_o , the wind speed (m s^{-1}), is computed from the logarithm law at the top of the canopy, and d is the average leaf diameter. The boundary layer resistance is connected in parallel through the entire sunlit leaf area, and in series with r_A . The resulting resistance to water vapor transport of the canopy, r_u can then be calculated from equation [8] (Thom, 1975).

2.4.2.2. The soil-plant-atmosphere numerical model

A one-dimensional numerical model developed by Avissar et al. (1986) was used to estimate the transpiration of adult avocado trees during the flowering and fruit set period. The model also predicts the representative temperature of the canopy. Modeled transpiration values were compared with those measured in the field under various climatic conditions. In addition, measured and estimated canopy temperatures was compared for each irrigation treatment.

The model simulates the energy fluxes encountered in the soil-plant-atmosphere system in the field. It is based on the previous works of Deardoff (1978) and Avissar and Mahrer (1982). In the model, the soil-plant-atmosphere system is divided into four different layers, considered as homogeneous in the horizontal plane: (i) soil, (ii) vegetation, (iii) air around vegetation and (iv) air above it. The soil layer is divided into thin vertical sub-layers, while the vegetation layer is treated as a bulk layer which partially covers the ground and is partially transparent to radiation. It is assumed that the heat storage in the plants and air can be neglected, since the heat capacity of these layers is small compared to the existing heat fluxes. Heat and mass fluxes are modeled at each layer to generate an energy balance equation, which has the general form of:

$$R_S + RL + E + H + S = 0 \quad [11]$$

and for moisture:

$$M_{in} - M_{out} = 0 \quad [12]$$

where R_S is the net flux of solar radiation absorbed by the layer, R_L is the net flux of long wave radiation, E , H and S are the latent, sensible and conductive heat fluxes, respectively. M_{in} and M_{out} are all the moisture fluxes entering or

leaving a specific layer. These energy and mass balance equations are solved by using an iterative procedure to obtain the unknown temperatures and humidities of the different layers.

For the soil surface and canopy, the energy balance equations correspond to:

$$Rn_s + E_s + H_s + S = 0 \quad [13]$$

$$Rn_v + E_v + H_v = 0 \quad [14]$$

where Rn is the net radiation, E is the flux of the water vapor or latent heat flux; H is the sensible heat flux; S is the soil heat flux, and the subscripts s and v denote the soil and the vegetation, respectively.

In order to account for different canopy densities, a shading factor is defined as the ratio between the plant shadow on the ground and the total ground area. This ratio is 1 for a completely covered surface, and 0 for a bare surface. To calculate transpiration, a function of the plant stomata reaction to environmental conditions (solar radiation, temperature, vapor pressure gradient and the leaf and ambient air, soil water potential, and CO_2 concentration) is included. For avocado, this function was developed with leaf conductance values determined by Sterne et al. (1977) for unstressed, well-watered and sunlit exposed leaves.

The sensible and latent heat fluxes between the atmosphere and the bottom layer (vegetation and soil, according to the value of the shading factor) were computed following Businger et al. (1971).

In the soil layer, the one-dimensional heat and moisture diffusion equations are:

$$C \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial z} \lambda \frac{\partial T_s}{\partial z} \quad [15]$$

$$\frac{\partial \theta_s}{\partial t} = \frac{\partial}{\partial z} D_\theta \frac{\partial \theta_s}{\partial z} + \frac{\partial}{\partial z} D_T \frac{\partial T_s}{\partial z} + \frac{\partial}{\partial z} Kh - E(r) + Ir(t) \quad [16]$$

where T_s is the soil temperature; t is time, z is depth, and C are the soil thermal conductivity and heat capacity, respectively, calculated according to de Vries (1963); θ_s is the soil volumetric water content; D_θ and D_T are the isothermal and thermal moisture diffusivities in the soil, calculated according to Philip and de Vries (1957); Kh is the hydraulic conductivity, obtained from the empirical power curve formula, based on the generalization of

Kozeny and Carman's approach (Willye and Gardner, 1968); $I_r(t)$ is the irrigation amount added at the top soil layer at the time of irrigation; and $E(r)$ represents a water uptake function proportional to the root distribution $r(z)$ in the soil, computed as:

$$E(r) = E_p r(z) / (\Delta z L \rho_w) \quad [17]$$

where E_p represents the total plant transpiration, Δz is the soil layer thickness, L is the latent heat of evaporation, and ρ_w is the water density. Equations [15] and [16] are solved numerically from soil surface to a depth of 1 m at which the diurnal variation of temperature is virtually eliminated and the moisture gradient is negligible.

III. MATERIALS AND METHODS.

3.1. Site description

The experiment was conducted for two years (1993-1994) in an avocado plantation (cv. Ettinger) of 287 fourteen-year-old trees planted at 6x6 m spacing in the Gilat Experimental Station in the northern Negev region of Israel. There were four experimental plots randomly distributed in the orchard with 15 trees per plot. The irrigation treatments were established in the field in September 1992 on plots that had previously been irrigated by two drip lines.

The Gilat Experimental Station is located at 31°20'N and 34°40'E, with an elevation of 150 m above sea level. Mean air temperatures are 14.1°C minimum in January and 25°C maximum in August, and the mean relative humidity in summer is 55-60%. Mean daily class A pan evaporation varies from 7 mm in April and September to 9 mm in July and August. The average annual rainfall is 250 mm, all of which falls during the winter months (November-April). In the Gilat site there are higher probabilities for the occurrence of hot and dry weather in the months of March till May, that coincide with the flowering and fruit set stages of avocado trees in Israel.

The soil of the experimental field is a loessial sandy loam with a uniform soil profile to a depth of 1.8 m and a bulk density of 1.45 mg/m³ (Steinhardt and Tomer, 1988). Volumetric water content at field capacity as determined in situ is 22.4, 30.1 and 31.0 % at soil depths of 0-30, 30-90 and 90-120 cm respectively. Wilting point is 10.2, 13.8 and 13.9 at the same depths. The soil water retention curve corresponds to $\psi = a\theta^b$, where $a = 7462372.8, 46579504.7$ and 38908702.3 for soil depths of 0-0.30, 0.30-0.90 and 0.90-1.20 m, respectively; $b = -3.778, -4.099$ and -4.010 for the same depths; ψ is the soil matric potential, expressed in centibars, and θ is the volumetric soil water content as a percentage. Mean electrical conductivity of the soil saturated extract (EC_e) to a depth of 1.2 m was about 1 mmho/cm. Cation exchange capacity (CEC) was 13.4 meq/100 g soil (Yaron et al., 1973). Saturated hydraulic conductivity of the soil is 0.84 cm s⁻¹.

3.2. Irrigation treatments

Two irrigation treatments with different wetted soil volumes were applied in the orchard, each on two experimental plots: (i) irrigation by one drip lateral located along the row of trees, wetting 25% of the soil surface, and (ii) irrigation by five drip laterals layed perpendicular to the row line, with one line positioned at the row line

and two lines positioned on each side, at distances of 1 and 2 m from the row, respectively. This irrigation treatment resulted in a soil wetting pattern similar to sprinkler irrigation, covering approximately 75% of the soil surface.

Irrigation was applied from March to November. Drippers of 3.7 l/h discharge rate were used in both irrigation treatments, placed 0.75 m apart along the lateral line. In both irrigation treatments, the amount of water applied per tree was $4 \text{ mm day}^{-1} \pm 15\%$. Considering the difference in wetted soil surface between the treatments, the frequency of irrigation was adjusted to prevent loss of irrigation water to deep soil layers in the treatment irrigated by one-drip line. In the single-drip-line treatment, irrigation was applied three times a week, while in the five-drip-line treatment, irrigation was applied once a week. The total amount of water applied per season was 896 mm.

Irrigation water from the National Water Carrier with an average electrical conductivity of 1.2 mmho/cm, SAR of 5 and Cl⁻ content of 7.5 meq/l was applied. Similar fertilizer dose was applied to both irrigation treatments (0.42 l N and 0.25 l Fe per tree per week).

3.3. Soil water content

Soil water content was measured with the neutron scattering method on two trees from each irrigation treatment. Eight aluminum access tubes were placed along a line perpendicular to the tree row. The spacing between the tubes was 0.55 m in the single-drip-line irrigation treatment, and 0.75 m in the five-drip-line irrigated plots, assuming that the two drip irrigation treatments would produce different wetting patterns. In the first year of the experiment readings were taken before and after the irrigation for the 5-line treatment, and only after the irrigation on the single-line treatment. In the second year the same schedule was maintained for the five-line treatment, while in the single-drip line treatment readings were taken only before the irrigation. In both treatments, five soil layers were monitored: 0-0.25 m; 0.26-0.55 m; 0.56-0.85 m; 0.86-1.15 m; and 1.16-1.45 m.

Soil water tension was monitored with electronic tensiometers (Tensiotronik 6001, Ami Ltd., Ashdod, Israel) that were installed on two plots at depths of 0.3 and 0.6 m, at 1 m distance from the trunk.

3.4. Root distribution

Avocado root distribution was examined using a modification of the profile wall method previously described by Gutafson et al. (1979), Levinson and Adato (1991) and Michelakis et al. (1993). Two months before

the first irrigation season started, trenches of 1 m depth and 3 m length were dug perpendicular to the tree line on one tree per plot in January 1993. Each trench was covered with a thick double black-plastic sheet to avoid the influence of external factors, and water pots were placed in the bottom of the trench in order to maintain an adequate internal humidity.

Roots were counted monthly from January 1993 to June 1994, on both walls of the trench using a 0.18-m grid. After every counting, a 3-5-mm-thick layer was removed from both trench walls in order to stimulate the appearance of new roots. The rate of root appearance was expressed as the daily number of root tips growing per square meter of trench wall.

3.5. Soil temperature

Soil temperature was measured with thermocouples placed between 0.30 and 0.70 m from the tree trunk and at depths of 0.15, 0.30, 0.45, 0.60 and 0.90 m. Two sets of 10 thermocouples were installed in the field on wetted soil under the canopy, and were connected to a multiplexer (Model AM 32, Campbell Scientific Inc., Logan UT., U.S.A). Average values were recorded automatically every half hour on a data logger (21X, Campbell Scientific, Logan UT., U.S.A).

3.6. Transpiration measurements

Avocado transpiration was determined by a calibrated heat pulse technique (Cohen et al., 1981; 1987). The sensor consisted of two probes of 3.1-mm diameter and 65-mm length, one with six microbead thermistors (GB 43 J1; Fenwal Electronics, Framingham, MA., U.S.A) and the other with only one thermistor. In the multisensor probe the thermistors were mounted on phenol fiber strips 0.8 mm thick and 3 mm wide, spaced 8 mm apart. The probe was molded in epoxy to form a cylindrical rod. At the thermistors locations the epoxy was replaced with cylindrical aluminum segments over a length of 1.5 mm, to improve thermal contact between the sensor and the wood. The multisensor probe was inserted radially into the trunk in a hole drilled 15 mm above the heater.

The heater consisted of an 80-mm-long section of a 0.8-mm-diameter nichrome wire enclosed in a stainless-steel sheath of 1.8 mm external diameter, with an electrical resistance of 0.312 Ω . Electrical connections on the heater body were sealed with epoxy to prevent water penetration. A heat-pulse was applied for 0.50 s with a corresponding heat output of 100 J. The holes for the heater and the sensors were drilled radially at a depth of 70 mm at low speed, using a guiding template to fix the relative position between the heater and the sensors. The holes for the probes were 0.1 mm wider than the diameter of the probe to avoid breakage during insertion. Probes were

radially inserted in two different directions of the trunk, at heights between 0.1 and 0.4 m above the ground. Lanolin was smeared on the probe before insertion, to avoid mechanical damage and to ensure a good thermal contact. The cross-sectional area of each annulus measured by the heat-pulse probe was determined from the stem radius, assuming a circular shape of the trunk.

Two data loggers (21X Campbell Scientific, Logan UT., U.S.A) connected to two multiplexer boxes (Ariel, Thermistor Junction Box, Model TJB 818, Tel Aviv, Israel) enabled measurements of 16 probes (a total of eight trees, four trees per treatment) at hourly intervals. Two lead-acid car batteries connected in series were used as a 24-V source to supply power to the heaters. The batteries were connected to a solar charger.

Avocado wet wood density (ρ) and specific heat (c) were determined from wood cores obtained with a Pressler borer (Suunto, Finland) at different depths from the bark. The measurements were taken on adjacent trees of similar diameter to the measured trees. Wood cores obtained from eight trees randomly distributed in the orchard were cut in the laboratory into 8-mm long sections, matching the spacing of the thermistors on the probe, and were placed in air-tight glass vials. The vials were later weighed, dried and reweighed, and ρ and c were determined. Values of ρ were calculated using: $\rho = \rho_w (1 + W_d)$ where ρ_w is the bulk density of the wood (kilograms of dry wood per cubic meter of wood including porosity) and W_d is the wood water content on a dry mass basis. Values of c were calculated following Marshall (1958) using $c = (c_w + W_d c_l)/(1 + W_d)$, where c_w is the specific heat of dry wood (1380 J kg⁻¹ °C⁻¹). Thermal diffusivity of the stem wood k , was determined by measuring t_m prior to dawn, when a null sap flow state was observed (Equation 4).

The heat-pulse technique was calibrated for avocado. For this purpose, one probe was inserted into a 5-year-old avocado plant growing in a 50-l pot that was placed inside a plastic chamber. The pot was covered with a wooden plate to minimize direct evaporation from the soil, and then it was placed onto a weighing balance (Model IC 64, Sartorius A.G., Goettingen, Germany). Sap flow measurements were compared with the rate of water loss by automatically weighing the pot to the nearest 0.1 g every 30 min.

3.7. Canopy water status

Leaf water potential was measured with a pressure chamber (Arimad 2, Kibbutz Kfar Charuv, Israel). Each set of measurements included four replicates of sunlit and shaded leaves of nearly the same age, on two trees of every treatment. Measurements were made periodically, between 8:00 and 14:00 h, during April and May 1994.

Canopy temperature was measured on one tree per treatment by means of two fixed-position infrared thermometers (Model 210 and Model 4000A, ± 1.0 °C accuracy, Everest Interscience, Fullerton, CA., U.S.A). Each instrument was placed at a distance of 4 m from the tree and to a height of 5.5 m from the ground, and directed at an angle to ensure that only foliage was contained within the circular field of view. Canopy temperature were automatically recorded every 7.5 min by a data logger (21X Campbell Scientific, Logan UT., U.S.A). In addition to the fixed-position devices, a hand-held infrared thermometer (Model 43s, focal plane 8 cm., Telatemp Corp., Fullerton, CA., U.S.A) was used to scan the canopy temperatures. Measurements were collected occasionally during April-May 1994, at three periods before noon. For each measurement, the average of at least 10 observations on sunlit leaves at different positions in the canopy was considered.

3.8. Climatic measurements

Air temperature and relative humidity (Model 201, Campbell Scientific, Logan, UT., U.S.A), global radiation (Kipp and Zonen, Delf, the Netherlands) and wind speed (Model O14A Met One, Sunnyvale, CA., U.S.A) were recorded automatically at a meteorological station located 300 m from the experimental site. Measures were made each minute, and hourly means were calculated. The height of measurement was 2 m above the soil surface.

These data were used to compute the potential transpiration according to a modified Penman-Monteith equation (Fuchs et al., 1987) and as inputs of the soil-plant-atmosphere model developed by Avissar et al. (1986).

3.9. The Soil-Plant-Atmosphere numerical model

The numerical model developed by Avissar et al. (1986) requires input data of the irrigation quantity, solar radiation, wind speed, air temperature and humidity; vegetation parameters such as leaf area index, photometric properties, root density distribution, and soil temperature distribution, texture, hydraulic conductivity and photometric properties.

The treatment of heat, mass and momentum fluxes above the canopy was done by assuming a quasi-steady-state approximation of these fluxes. The plant canopy was described as one bulk layer. Energy fluxes, ambient air temperature and moisture within this layer were partitioned according to a shading factor (determined by the ratio of the shaded area to the total surface area) and the leaf area index (LAI). The avocado LAI was estimated from preliminary measurements made during the summer with a ceptometer (Sunlick, Decagon, Pullman, WA, U.S.A) (unpublished data). Leaf conductance was taken from the values published by Sterne et al. (1977) for unstressed,

well-watered and sunlit exposed leaves. Meteorological data of air temperature, air relative humidity, global radiation and wind speed, averaged every hour, were used as inputs to the model.

IV. RESULTS.

4.1. Distribution of soil water content

Figure 1 shows the distribution of soil water content with distance from the tree row for the one-dripper line treatment, measured on three dates during the experimental period: (a) June 13, 1993; (b) July 25, 1993 and (c) May 22, 1994. Data shown in the figure correspond to the average soil water content measured on two trees 1 day after the irrigation. The asymmetrical distribution of soil water content between the two sides of the row line was due to the location of the irrigation line on the right-hand side of the tree row. A marked decrease of soil water content with increasing distance from the row line was observed at all depths, and particularly at 0.25 m. High soil water content was maintained only in a limited region, extending about 0.50 m on each side of the dripper line.

In the light of the high frequency of irrigation applied to this treatment, it may be considered that the pattern of water distribution in the soil did not vary significantly between irrigations.

Figure 2 shows the distribution of average soil water content with distance from the row line, for the five-dripper line irrigation treatment, measured on three dates during the experimental period: (a) August 19, 1993; (b) November 4, 1993, and (c) May 25, 1994. Data correspond to measurements taken 6 days after irrigation. Even though, higher water contents were observed in the soil, in comparison with those measured 1 day after the irrigation in the one-dripper line treatment.

Figure 3 presents the distribution of average soil water content measured in the same treatment 1 day after irrigation on: (a) August 21, 1993; (b) November 6, 1993, and (c) May 27, 1994. In this treatment a gradual reduction of soil water content with increasing distance from the trunk was also observed, but this reduction was less pronounced than in the treatment irrigated by one-dripper line. Comparison between the patterns of soil water distribution observed 6 days after irrigation (Fig. 2) and 1 day after irrigation (Fig. 3) suggests that water was extracted mainly from the two upper soil layers (0-0.25 m and 0.26-0.55 m), with only a little water extracted from a depth of 0.85 m. Measurements obtained from deeper soil layers did not show considerable variations in soil water content with time after irrigation.

In the five-line treatment the distribution of irrigation water in the soil was more extensive than in the one-line treatment: up to approximately 2.25 m from each side of the row line, compared with only 1.10 m. At longer distances from the row line (>2.25 m) soil water content did not vary significantly with time after irrigation.

Figure 1a

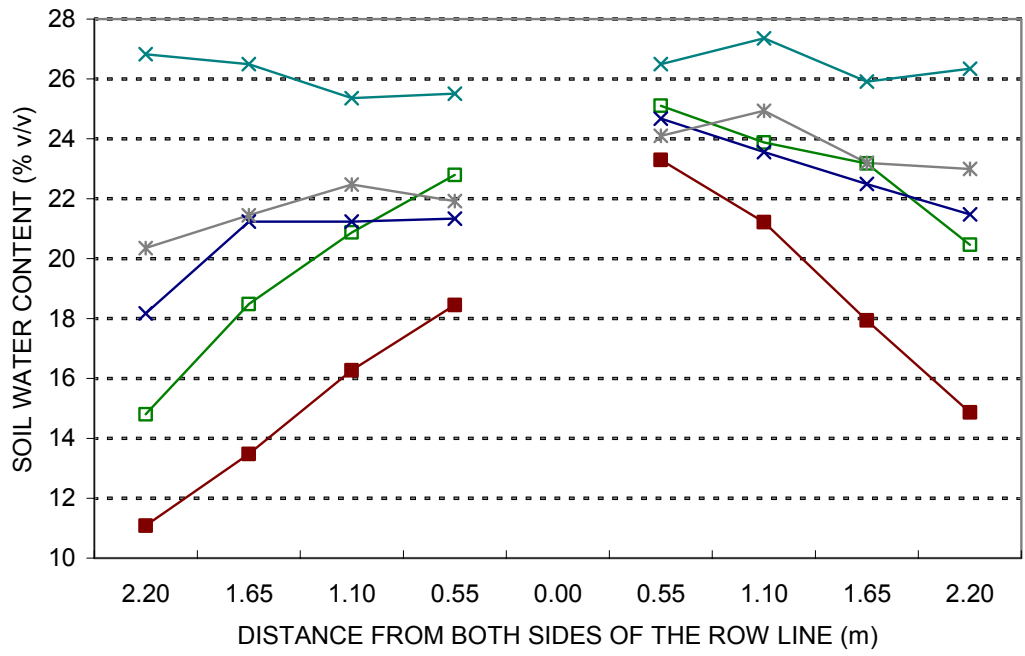


Figure 1b

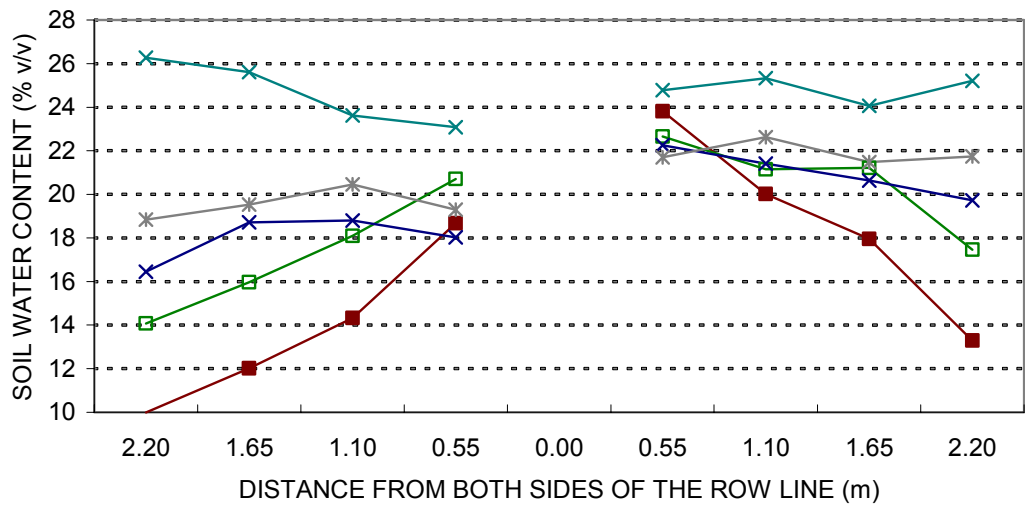


Figure 1c

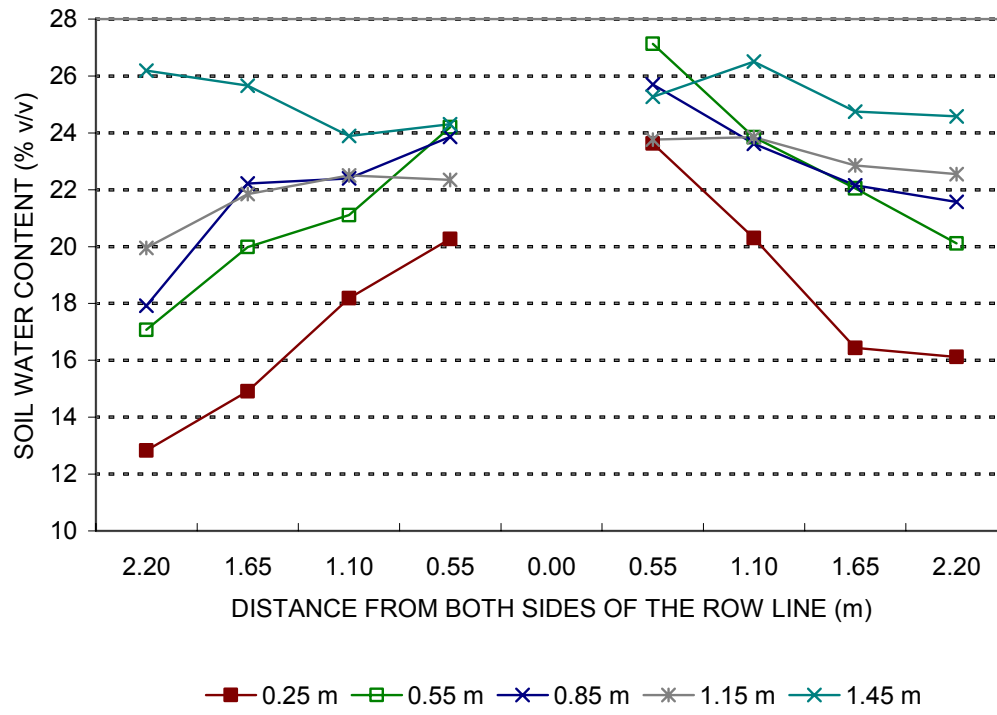


Figure 2a

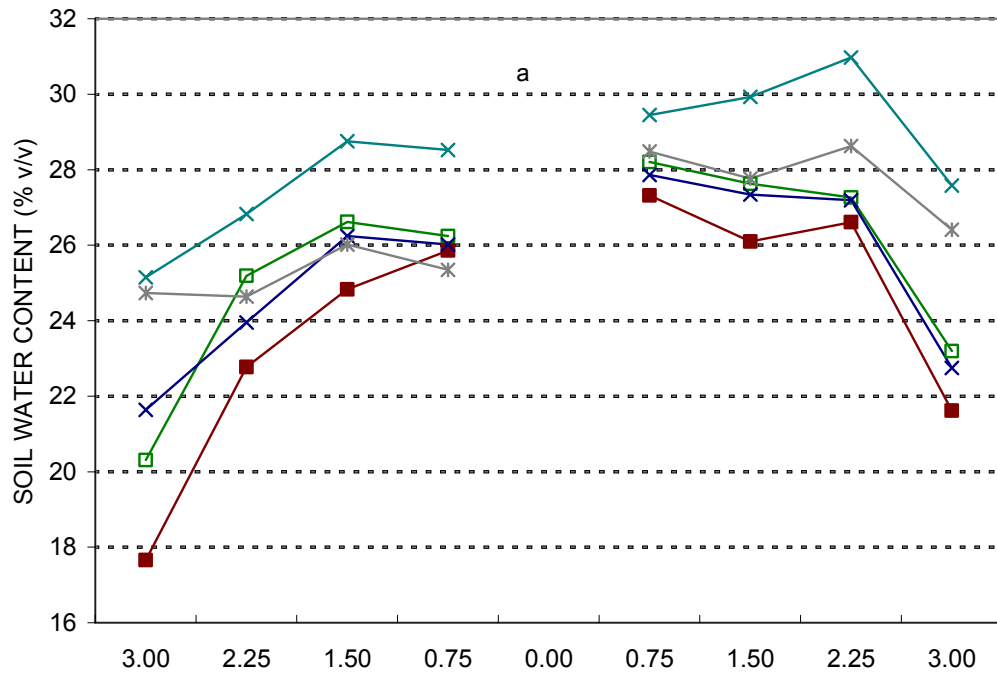


Figure 2b

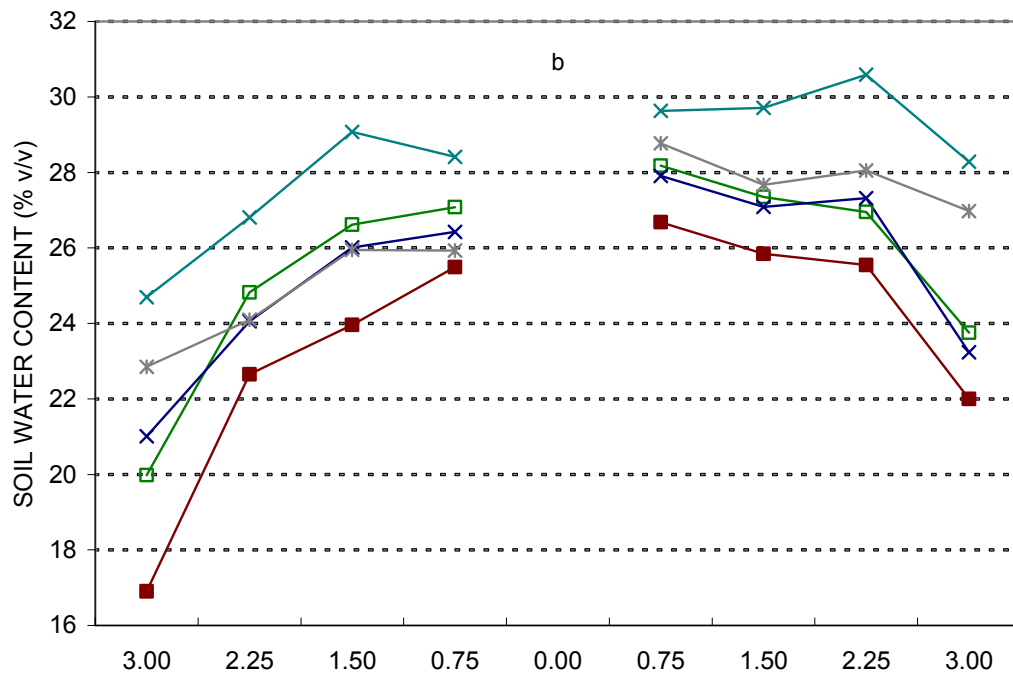


Figure 2c

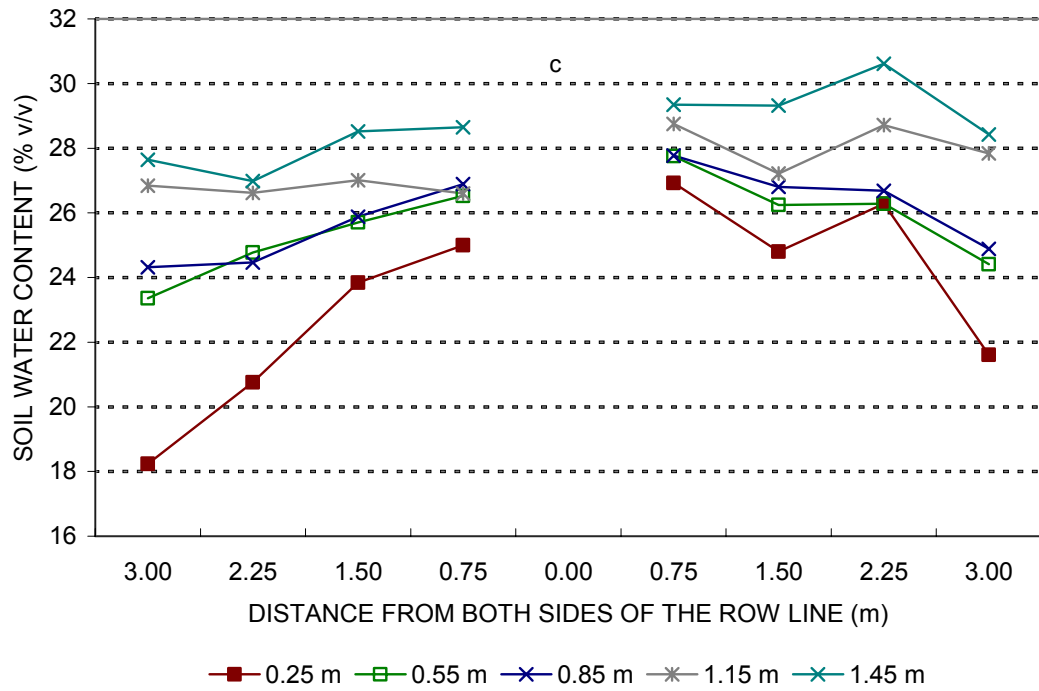


Figure 3a

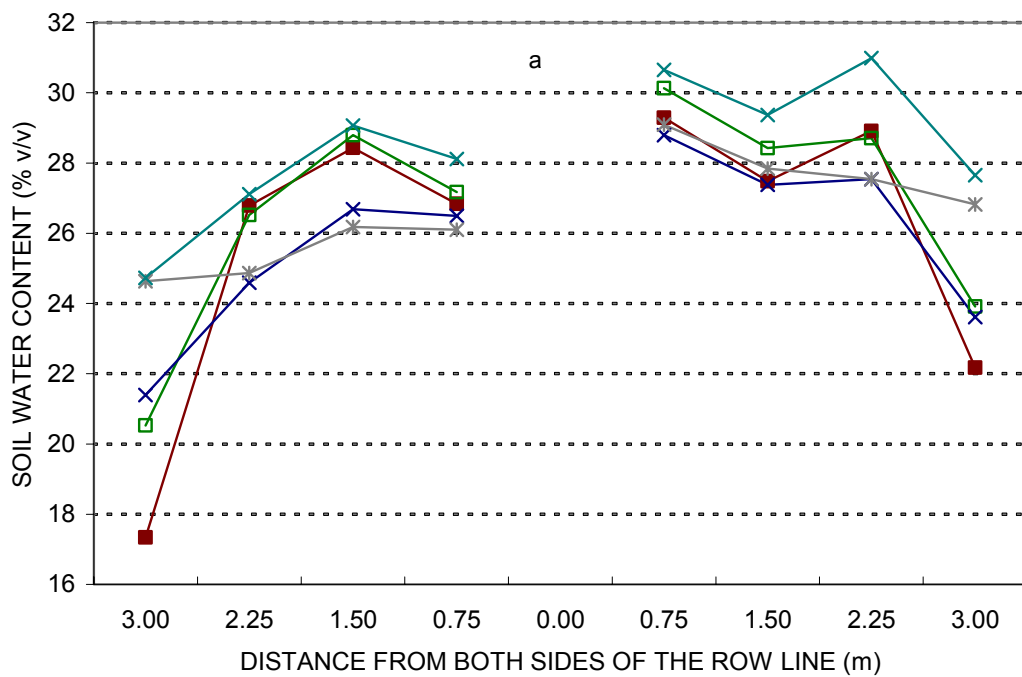


Figure 3b

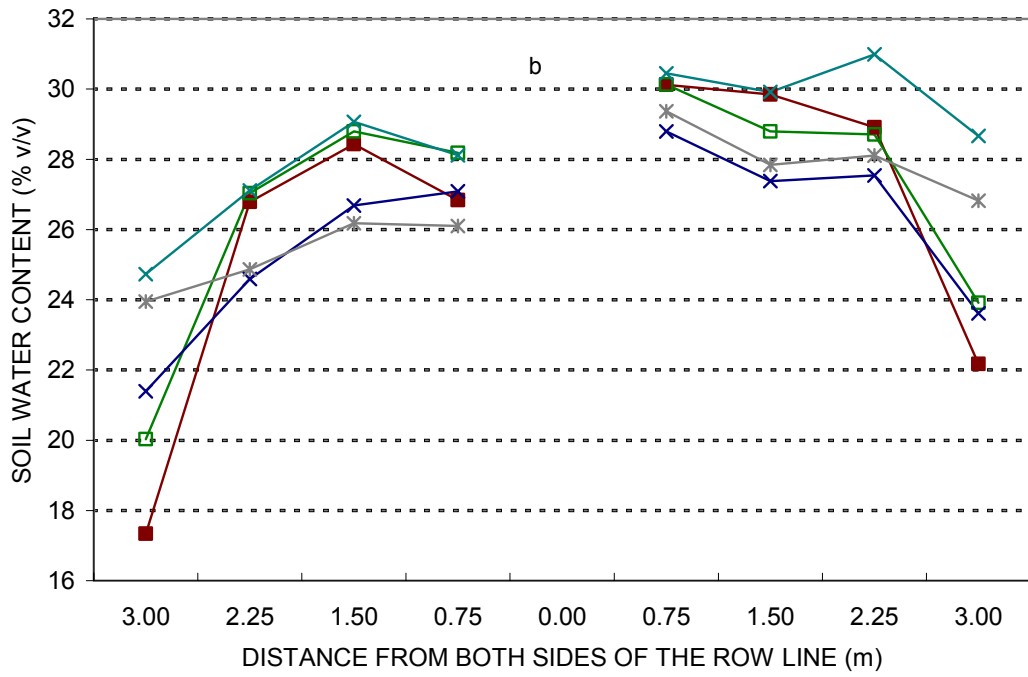
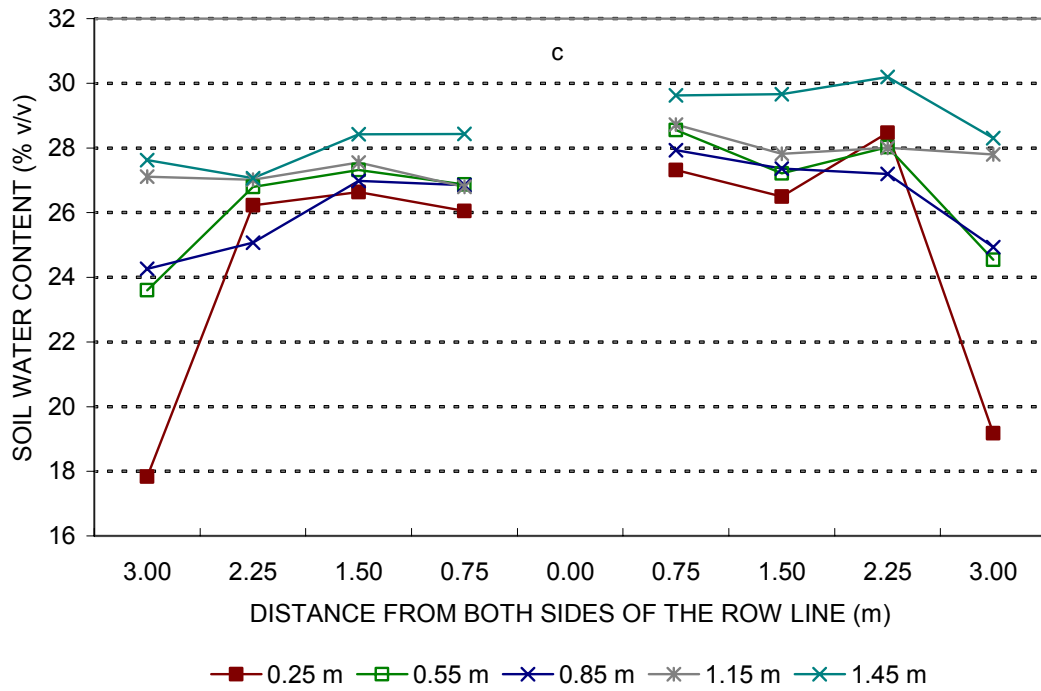


Figure 3c



4.2. Distribution of the root system

The seasonal trends of root tip appearance for both irrigation treatments during 1993 are given in **Figure 4**. Data correspond to the root tips observed on both walls of the trench, up to 2.50 m from the trunk and 0.90 m depth. During March-April, the one-line irrigation treatment showed a higher root growth rate than the treatment irrigated by five lines. From May onwards, a visible response of root growth to the enlarged wetted soil volume was observed, with more root tips appearing in the treatment irrigated by five lines. The figure shows three peaks of root growth: a relatively low peak in March, followed by the largest one in June, and a third in October-November. The average rates of root tip appearance during 1993 were 3.93 and 3.35 tips m⁻² day⁻¹ for the five- and the one-line irrigation treatments, respectively. It is assumed that in this, the first season, the treatment effect on root distribution was not fully expressed.

Figure 5 presents the variation of the annual average rate of root tip appearance with distance from the row line, as measured in 1993. The reduction in root appearance with increasing distance from the row line observed in both treatments is explained by the decrease in soil water content with distance from the row line, as discussed above (Figures 1, 2 and 3). However, the single-line irrigation treatment developed more roots in the first 0.50 m from the row line, due to a higher soil water content close to the irrigation line. At longer distances from the trunk the rate of root appearance was larger for the five-line irrigation treatment.

Figure 6 shows the variation of the annual average rates of root tip appearance with depth observed during 1993 in both treatments. Analysis of the data indicated that over 70% of the roots were concentrated in the first 0.50 m of the soil, in both irrigation treatments, while below 0.70 m depth, low rates of root appearance were observed in both treatments. This finding confirms earlier reports on the shallow distribution of avocado roots (Gutafson et al., 1979; Kalmar and Lahav, 1977; Levinson and Adato, 1991; Michelakis et al., 1993).

In the second irrigation season clear differences between the treatments in the root distribution pattern were observed. **Figure 7** shows the variation of the average rate of root tip appearance with distance from the row line, measured in both treatments in May-June 1994, when root activity was at its maximum. Vertical lines indicate the distance at which the end of the wetting front was found for each irrigation treatment (1.10 m from the trunk in the one-dripper line treatment, and 2.25 m distance for the treatment irrigated by five-dripper lines). Both treatments showed a diminishing root appearance with increasing distance from the row line. The one-dripper line treatment developed a greater number of roots in the first 0.50 m from the row line than did the five-dripper line treatment. However, at larger distances from the row, the treatment irrigated by 5-dripper lines showed higher rates of root tip

appearance. The average rate of root appearance during the analyzed period was higher for the five-drip line treatment: 8.14 root tips $\text{m}^{-2} \text{day}^{-1}$, compared with only 5.54 root tips $\text{m}^{-2} \text{day}^{-1}$ in the one-dripper line treatment.

Table 1 shows the average percentage of total root tips at five depths in the soil, measured in two replications of each irrigation treatment during May-June 1994. The trees irrigated by five lines developed more roots in the first 0.36 m depth, due to the larger wetted soil surface. In both treatments, over 70% of the total roots were concentrated in the uppermost 0.50 m below the soil surface. The single-line irrigation treatment showed a higher root concentration at 0.54 m, due to deeper water percolation than in the five-line treatment.

Figure 4

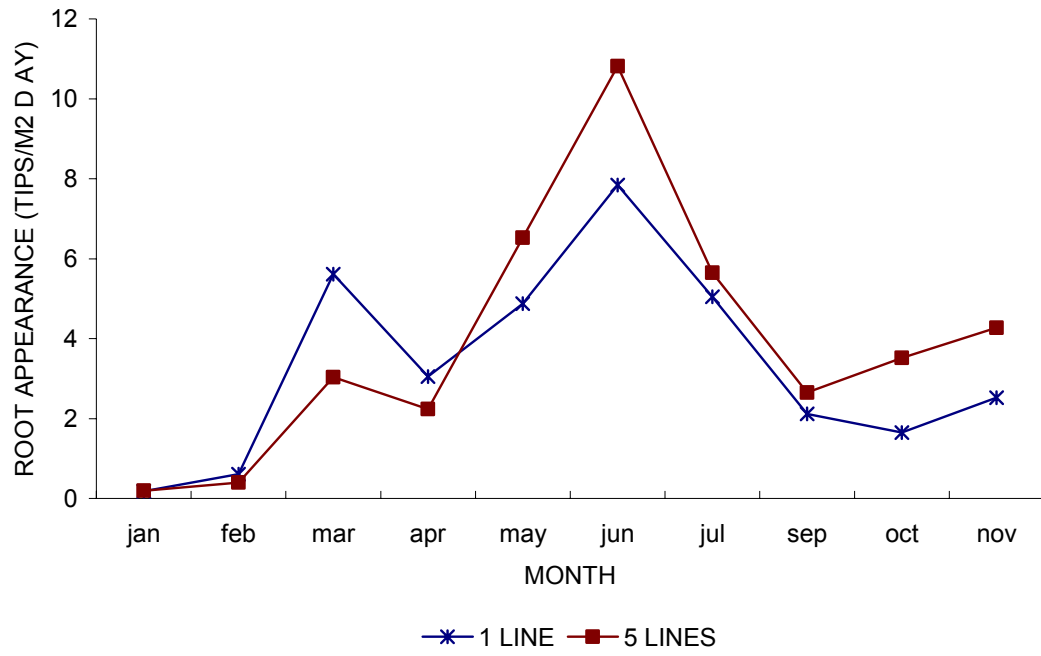


Figure 5

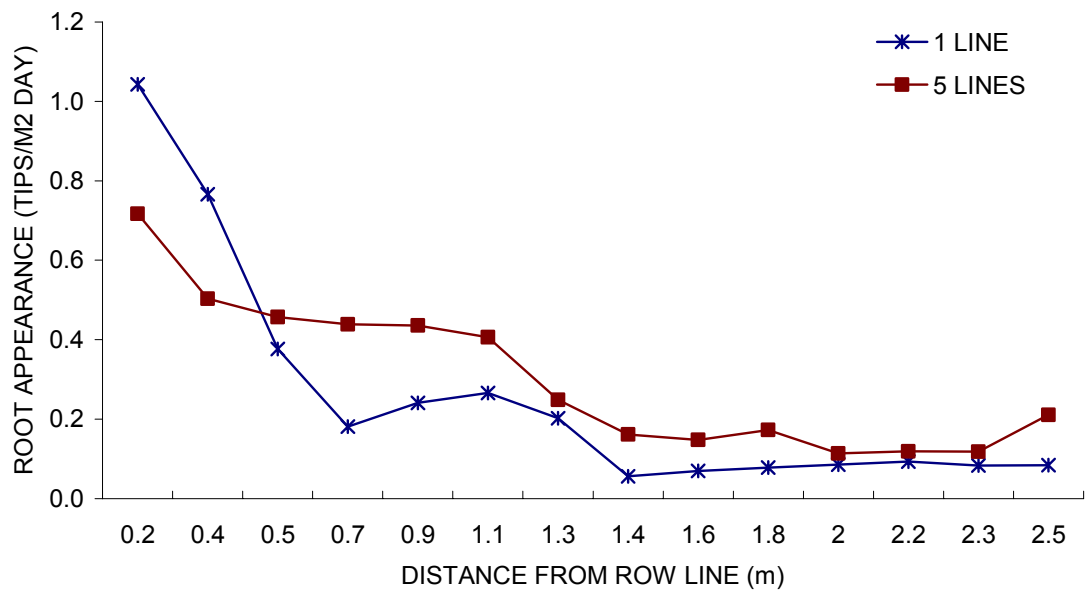


Figure 6

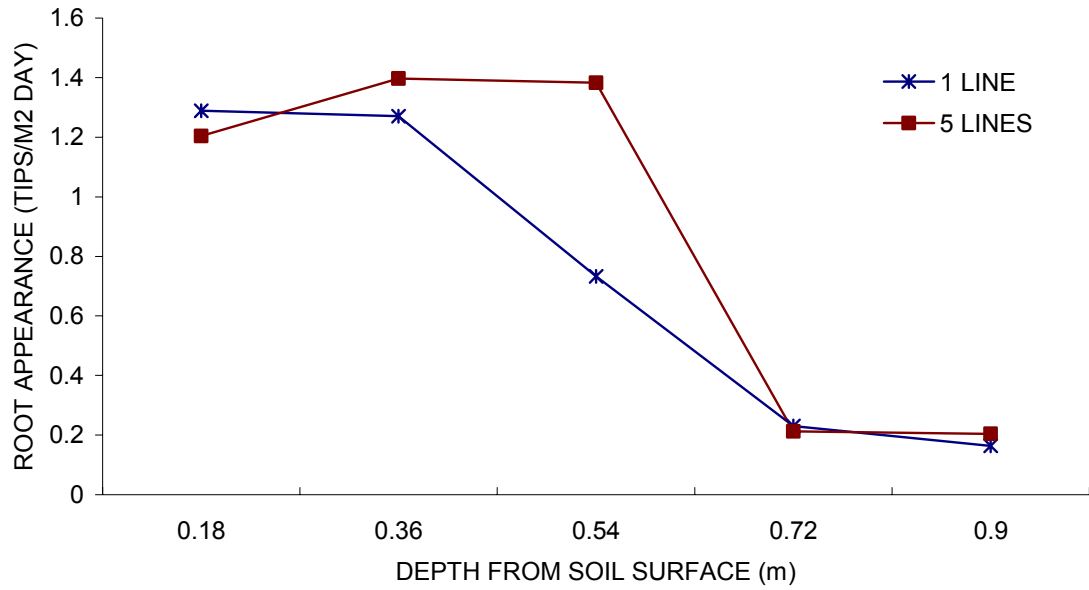


Figure 7

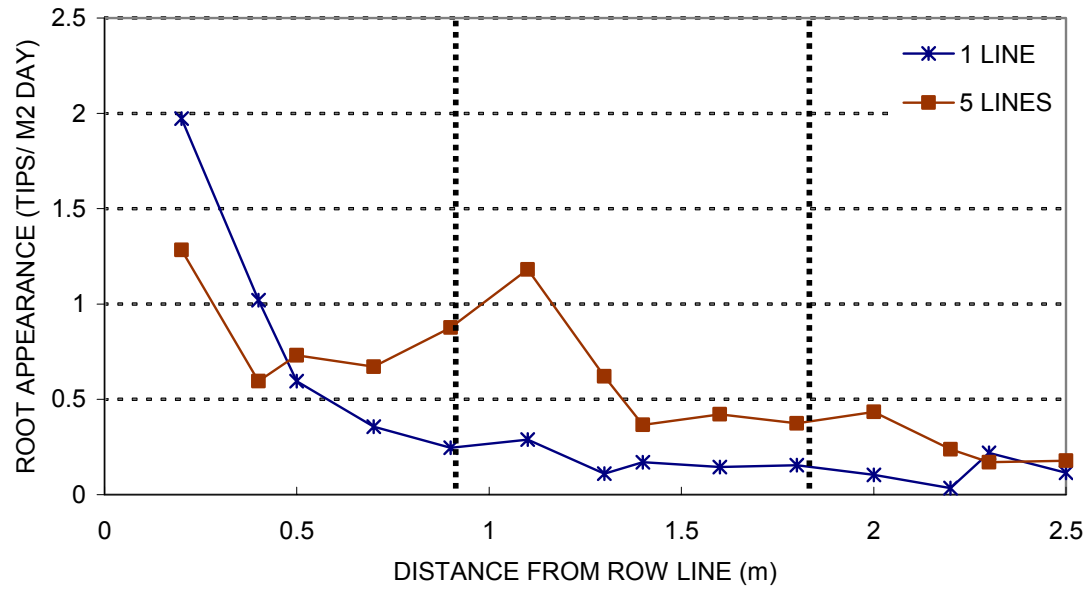


TABLE 1. Average percentage of roots at five soil depths, observed up to 2.5 m line, in both irrigation treatments during May-June 1994.

from the row

Depth (m)	Irrigation with five lines	Irrigation with one line
0.00-0.28	47.6	37.6
0.29-0.36	32.8	30.9
0.37-0.54	9.4	24.4
0.55-0.72	5.3	5.5
0.73-0.90	4.9	1.6

The results of these observations of the effects of the two irrigation treatments on avocado root distribution suggest that enlargement of the wetted soil area caused active roots to be distributed over a larger soil volume and accelerated their growth rate.

4.3. Soil temperature and root growth

The seasonal trend of soil temperature in 1993 at five soil depths under the canopy is presented on **Figure 8**. At the beginning of the irrigation season (March) soil temperature was around 18°C, which is the minimum required for promoting avocado root growth in spring (Whiley et al., 1988a). Towards the summer (May-June) soil temperature increased to 20-22°C, which is within the optimum range reported for root growth of avocado seedlings (Lahav and Trochoulis, 1981). Also during this period, temperature differences between soil layers became more pronounced. Maximum soil temperature (25- 26°C) was registered at all depths in July-August.

Figure 8

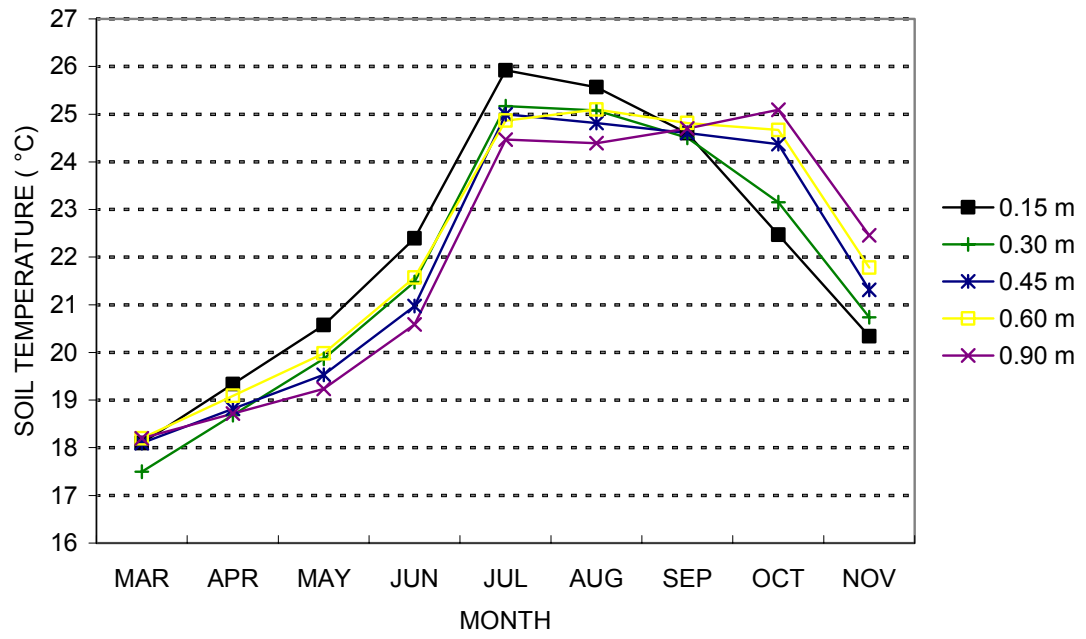


Figure 9 presents the seasonal curve of average rate of root tip appearance for the five-drip line irrigation treatment, and the monthly variations of maximum soil temperature measured at 0.30-m depth during 1993. The maximum rate of root tip appearance occurred in June, while the maximum soil temperature was recorded 1 month later, in July. A reduction in root tip appearances was observed in April (peak anthesis) irrespective of the soil temperature trend. A similar reduction in root tip appearances was also observed in April 1994. This finding is probably associated with the effect of internal tree factors which limit avocado root growth during this period.

Previous studies have reported the detrimental effect of high soil temperatures ($>30^{\circ}\text{C}$) on avocado root growth (Lahav and Trochoulis, 1981). Periods of high air temperature may increase the temperature in shallow soil layers, where many fine avocado roots grow under the leaf cover. **Figure 10** compares the diurnal course of the difference between air temperature and soil temperature at 0.30 m ($T_a - T_s$), measured on a day with high T_p (14.59 mm day⁻¹) and on a day with lower T_p (7.69 mm day⁻¹) in April 1994. The maximum differences between air and soil temperatures observed after noon were 10°C on the day with low T_p , and 22°C on the day with high T_p . However, even under severely hot weather soil temperature did not exceed 20°C and consequently did not limit avocado root growth at 0.30 m depth. This finding was attributed to the fact that soil temperature was measured beneath the canopy and under a thick layer of dry leaves which prevented excessive heating of the upper soil layers.

Figure 9

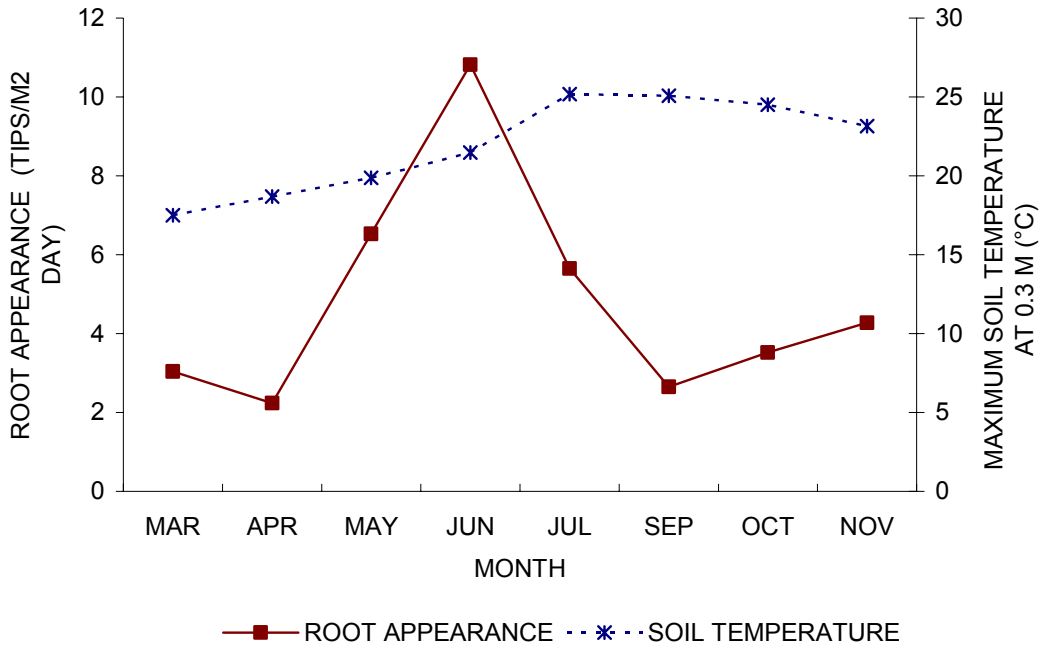
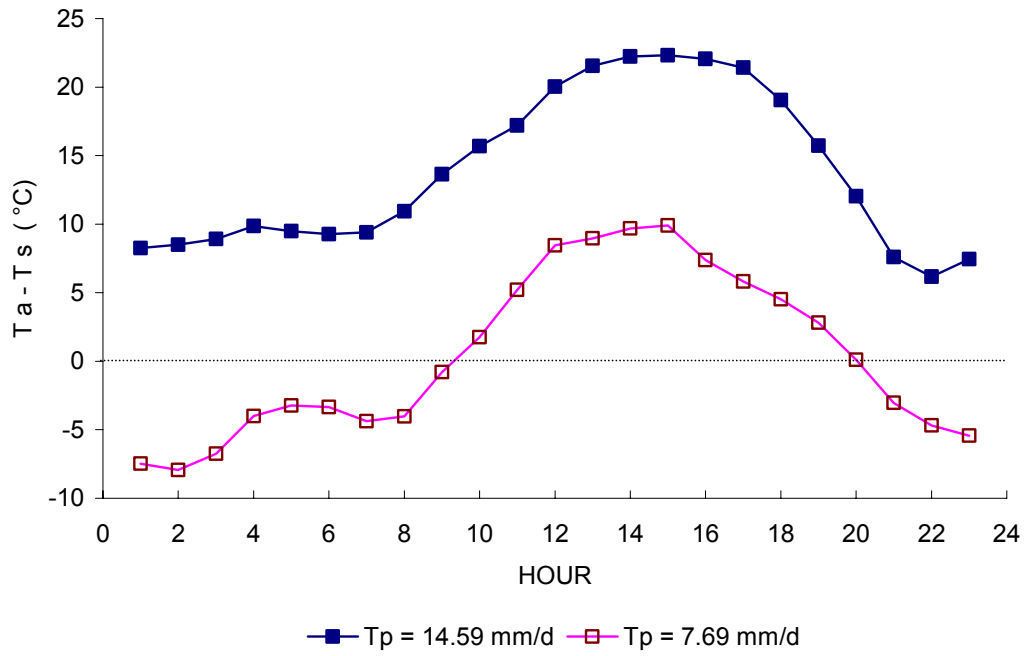


Figure 10



4.4. Adaptation of the heat-pulse technique to measure sap flow in avocado

A significant correlation was found between the measured sap flow and the actual transpiration rate, as measured by weight loss, as seen in **Figure 11**. The slope of the curve indicates that sap-flow measurements underestimate actual transpiration by 56%.

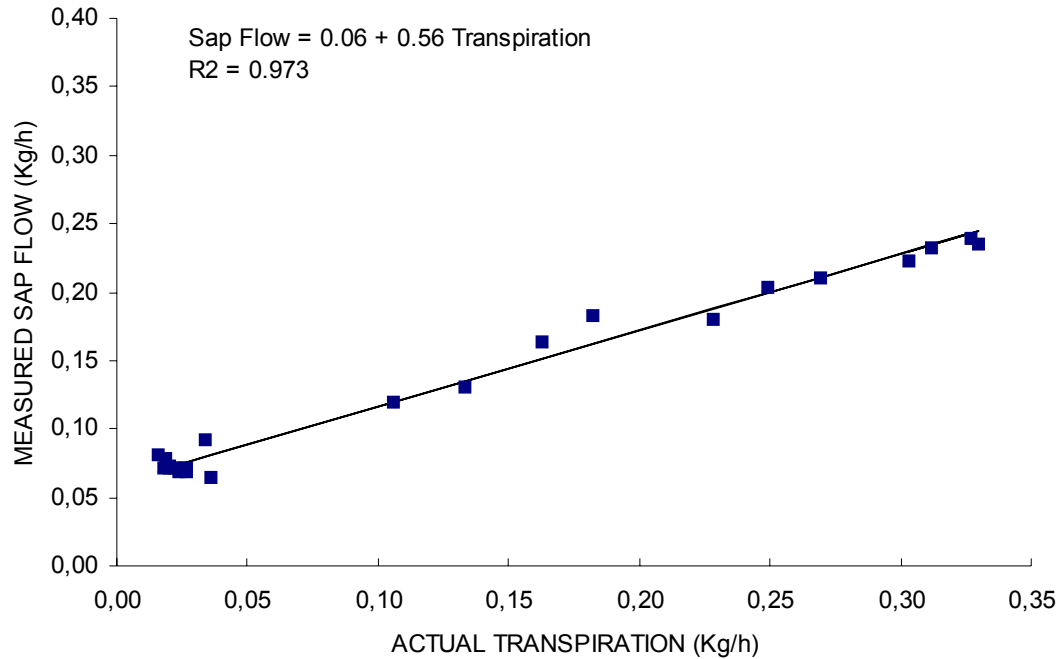


Figure 11. The relationship between sap flow computed from heat-pulse measurement and actual transpiration obtained by weight loss in a 5-year old avocado tree.

Physical parameters of wet avocado wood which are required for the calculation of transpiration rate from sap flow measurements are presented in **Table 2**. The table shows the average values of water content (W_d), density (ρ) and specific heat (c) at a series of depths from the bark, based on wood cores sampled from eight avocado trees in the orchard. Large changes on water content, density and specific heat were found in avocado wood with increasing depth from the bark. Water content of the heartwood, identified by the inner wood cores, was lower than that of the sapwood (external wood cores). This is a major reason for the large differences in other physical properties between sapwood and heartwood. The average density and specific heat of the wet avocado wood were 874 kg m^{-3} and $2619 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$, respectively.

TABLE 2. Average values of wet avocado wood physical properties used for field measurements of sap flow rate by the heat-pulse technique.

Depth (cm)	W_d (kg kg ⁻¹)	ρ (kg kg ⁻¹)	C (J kg ⁻¹ °C ⁻¹)
0.0-0.8	0.83	1535	2652
0.9-1.6	0.79	1567	2619
1.7-2.4	0.81	1580	2635
2.5-3.2	0.70	1440	2539
3.3-4.0	0.89	1712	2699
4.1-4.8	0.73	1561	2569
4.9-5.6	0.75	1613	2583

The determination of sap flow in trees by the heat-pulse technique is based on the measurement of the time elapsed between the application of the heat-pulse and the occurrence of maximum temperature 15 mm above the heater (t_m in equation 3). Higher t_m values indicate a lower heat conduction, i.e., lower sap-flow velocity. **Figure 12** shows the daily course of t_m values measured in one tree with a six-thermistor heat-pulse sensor, and a schematic diagram of the cross-section of the trunk showing the positions of the six thermistors of the probe. Sap-flow velocity varies markedly with depth below the cambium, as in most tree species. The inner thermistors of the heat-pulse probe registered lower sap velocities, represented by higher t_m values, because they were located in the heartwood.

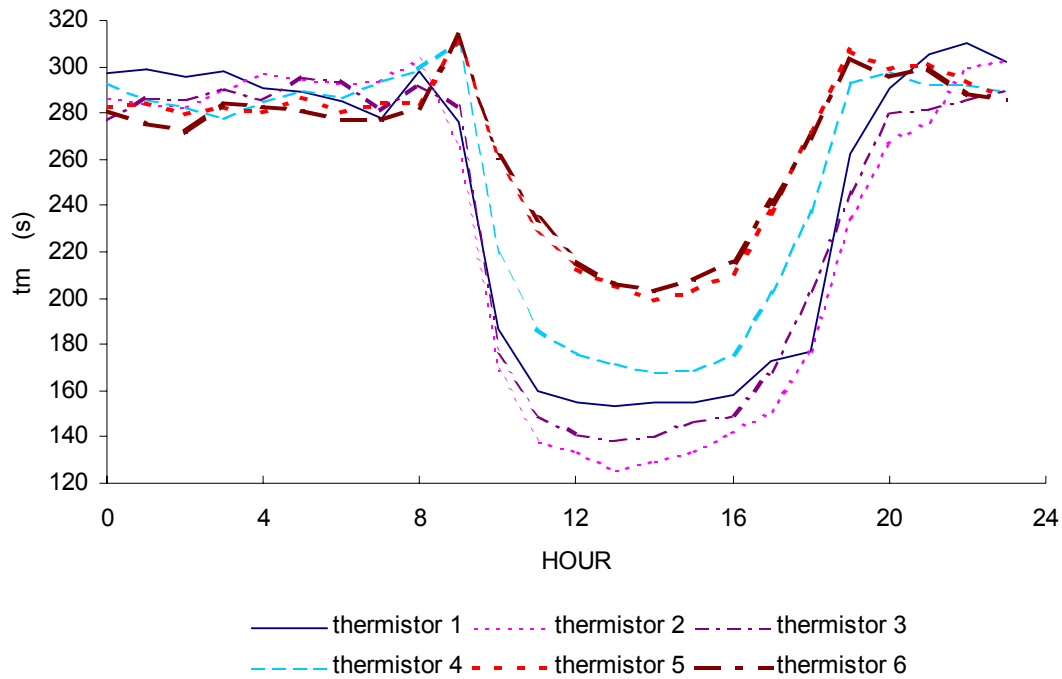


Figure 12. Daily course of t_m measured with a six-multi thermistor heat-pulse sensor in the stem of an avocado tree. Schematic diagram of the cross-section of the trunk, showing the positions of the six thermistors.

The spatial distribution of sap velocity across the trunk cross-section of mature avocado trees was extremely inconsistent between different sides in the same trunk and between trunks of different trees. An extreme example of the differences in sap velocity is shown in **Figure 13**, which shows large differences in sap velocity among the

three sides of the trunk, in variation of sap velocity with depth under the bark . At the southern side, for instance, sap velocities at depths of 24-32, 32-40 and 40-48 mm were close and relatively high (Fig. 13a). In contrast, sap velocity at the same depths in the northern side (Fig. 13c) was much lower, and at 40-48 mm it was zero. The orientational distribution of sap flow measured in other trees differed from the one given in Fig. 13, and varied widely among trees. This spatial variability of sap velocity indicated the need for more measurements to enable accurate estimation of avocado tree transpiration to be made. For routine field measurements two probes were inserted, one on each side of the trunk on each experimental tree. However, in the case of the sap-flow velocity distributions given in Fig. 13a and 13b, there is some doubt as to the exact sapwood area which must be considered in the computation of total sap flow in the trunk. This particular pattern of sap conduction was observed for about 25% of the measured points.

Macro-anatomical observations of sap-conducting elements in pieces of young branches, performed in the laboratory of Dr. Eli Zamski (Department of Botany, Faculty of Agriculture, The Hebrew University of Jerusalem, Rehovot), indicated that the conducting elements of avocado wood are organized as in diffuse-porous sapwoods, with vessels of 50-100- μm diameter scattered throughout the functioning sapwood. Vessels were also observed in the central cores of young branches, indicating the possibility of water conduction in this zone if sapwood is present. This finding supports the results presented in Figures 13a and 13b.

As reported for other fruit tree species (Edwards and Warwick, 1984) the accuracy of the heat-pulse method can be strongly impaired as a result of progressive physical deterioration of the measurement holes, due to the reaction of the tree to the wound. In avocado, there was no evidence of wound reaction affecting the holes where probes were inserted. Comparison of heat velocity measurements obtained from holes at different seasons showed no physical deterioration, even 2 years after the hole had been drilled. In the spring of the second measurement season, a certain green, soft tissue growth covering the first 2-3 mm of some of the holes was observed. This tissue was easily removed before inserting the probes, without affecting the physical condition of the hole or the accuracy of the measurements.

Figure 13a

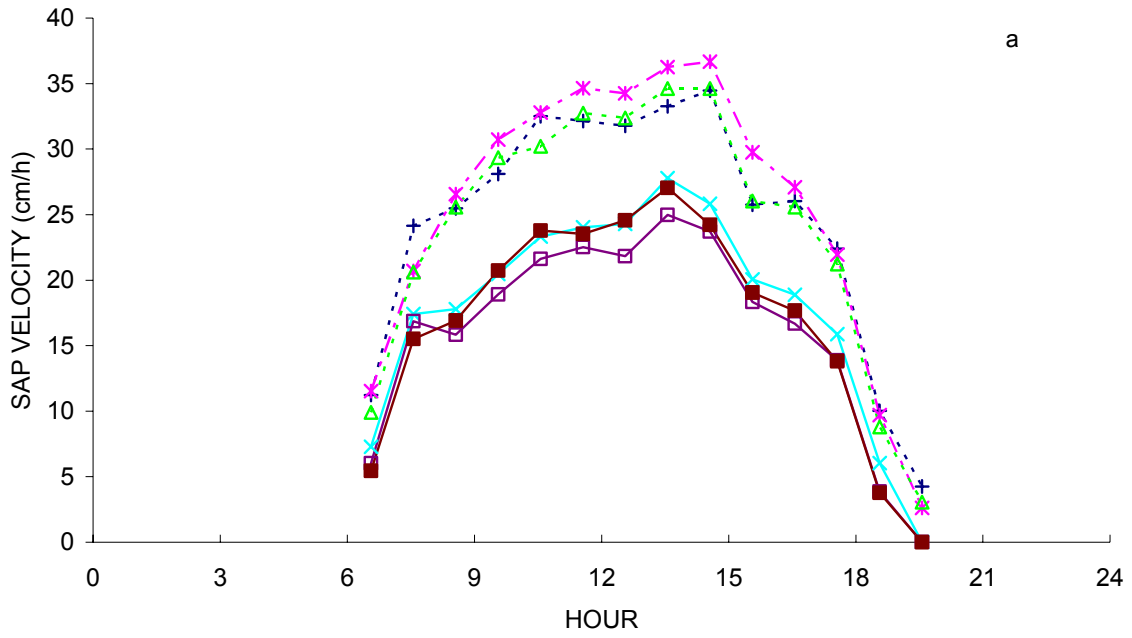


Figure 13b

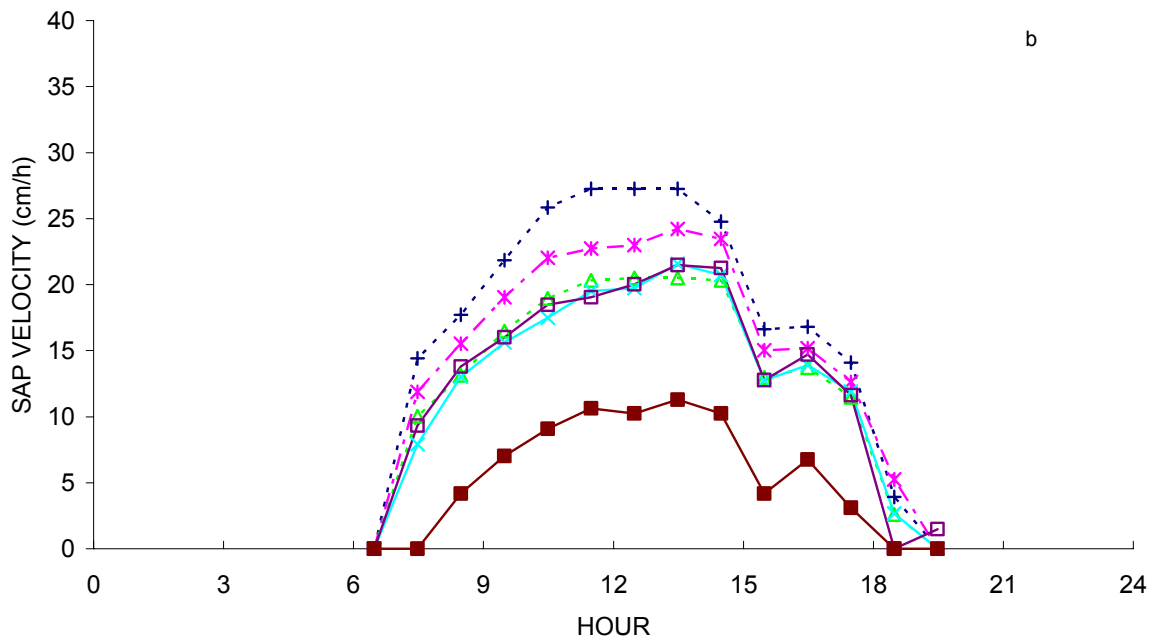
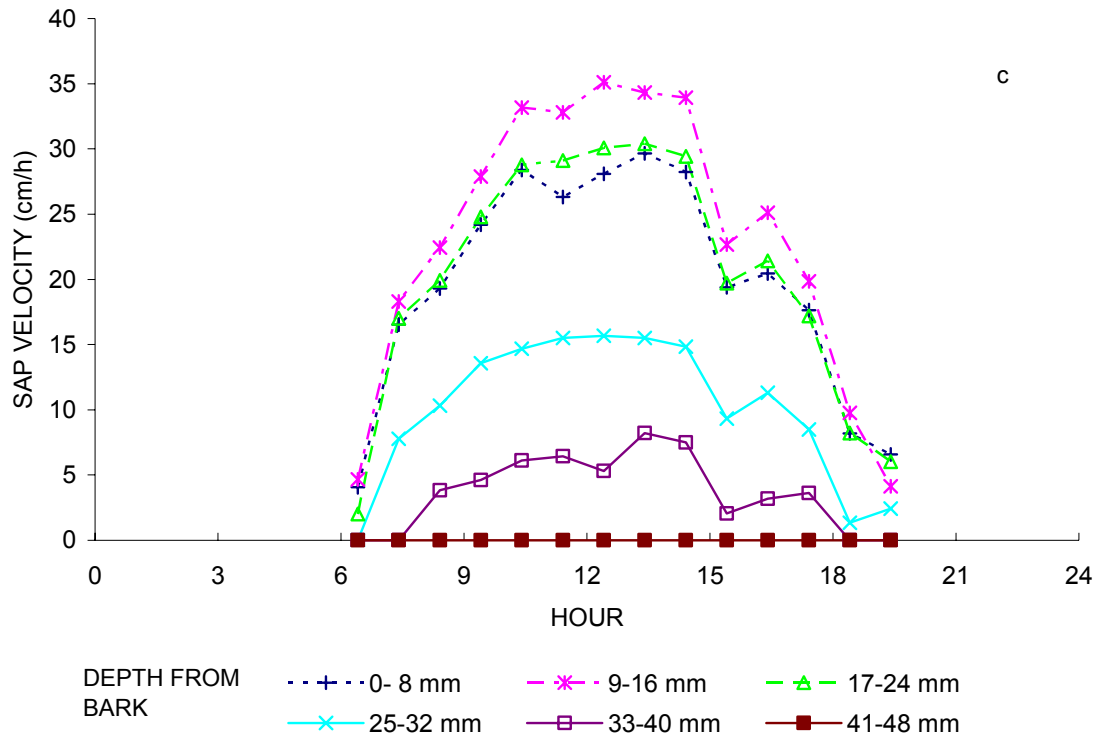


Figure 13c



4.5. Effect of wetted soil volume on transpiration rate

Transpiration rate varied considerably among trees, because of differing tree sizes and previous pruning treatments. Therefore, differences in the absolute values of transpiration observed between the treatments reported in the present study should be considered as a result of both the size of the selected trees and the treatment.

Figure 14 shows the daily course of transpiration rate (T) measured in both irrigation treatments on May 13, 1994. The data correspond to individual transpiration measurements on four trees per treatment. There was a greater variability in transpiration among trees in the treatment irrigated by five-drip lines, with trees nos. 6 and 8 showing higher values than trees nos. 7 and 5. This variability was attributed to differences in size among the trees. Average transpiration in the five-line irrigation treatment was higher (51.1 l day^{-1}) than in the single-line treatment (47.8 l day^{-1}), but the standard deviations were as large as 19.3 and 4.4 l day^{-1} per tree, respectively, for the same treatments.

Figure 15 presents the course of the daily transpiration rate from March 21 till June 10, 1994, i.e., in the flowering and fruit set period, measured on each of four trees per irrigation treatment. If data from tree no. 6 of the five-line treatment are omitted as they represent exceptional values, no clear differences between the irrigation treatments in transpiration level are found. T for the period ranged between 30 and 100 l day^{-1} per tree for both treatments. This range was similar to the transpiration rates observed during the same period in the first irrigation season, when the effect of the irrigation treatments on transpiration rate was not yet expressed. No clear evidence of differences in transpiration rate between trees irrigated by five lines and those irrigated by a single line were observed in the second irrigation season.

Figure 14

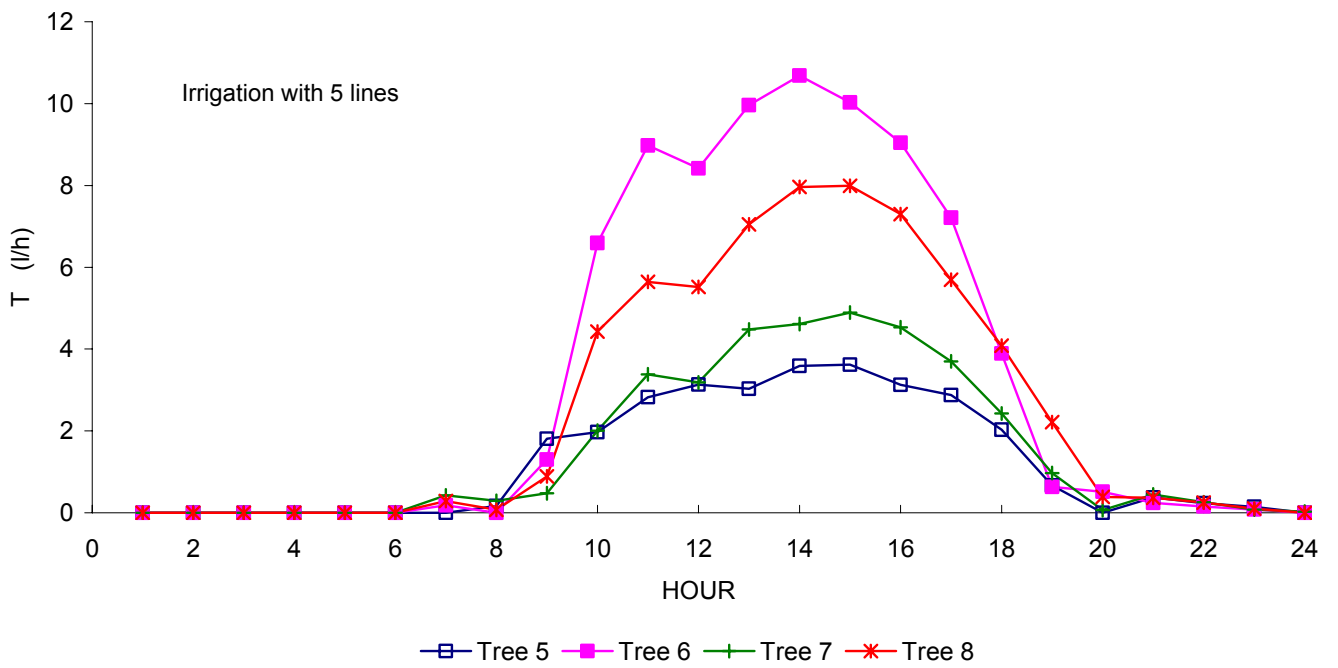
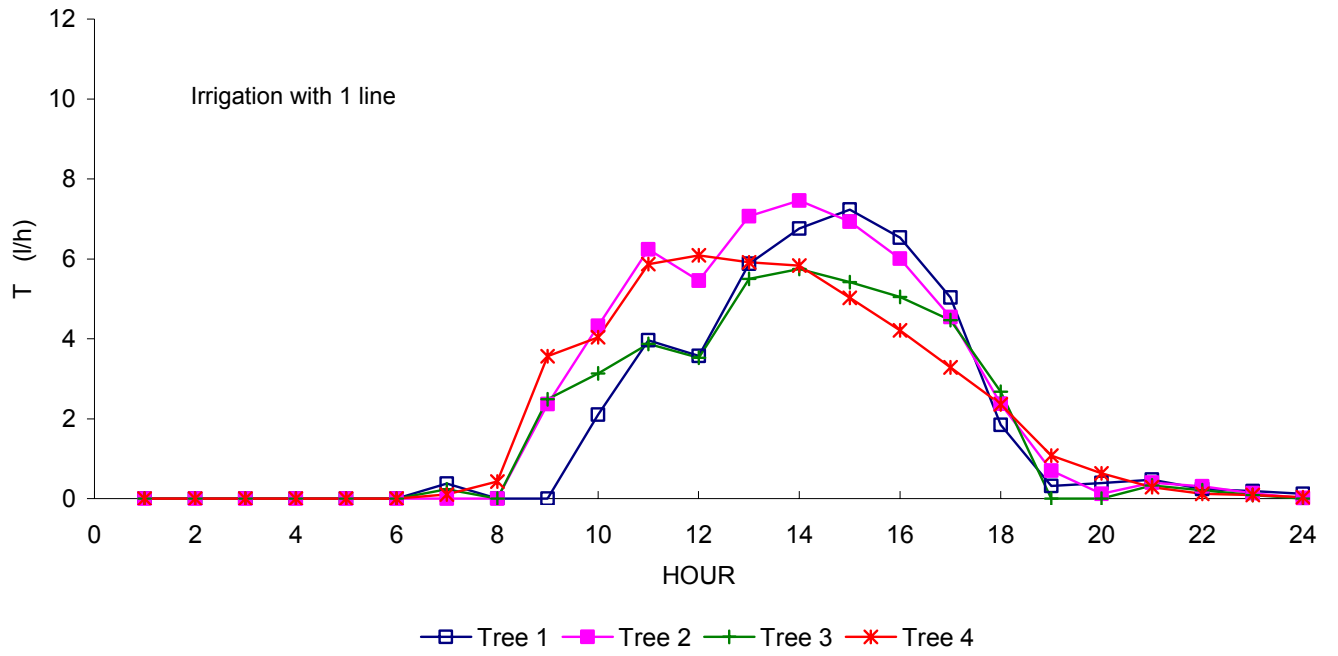
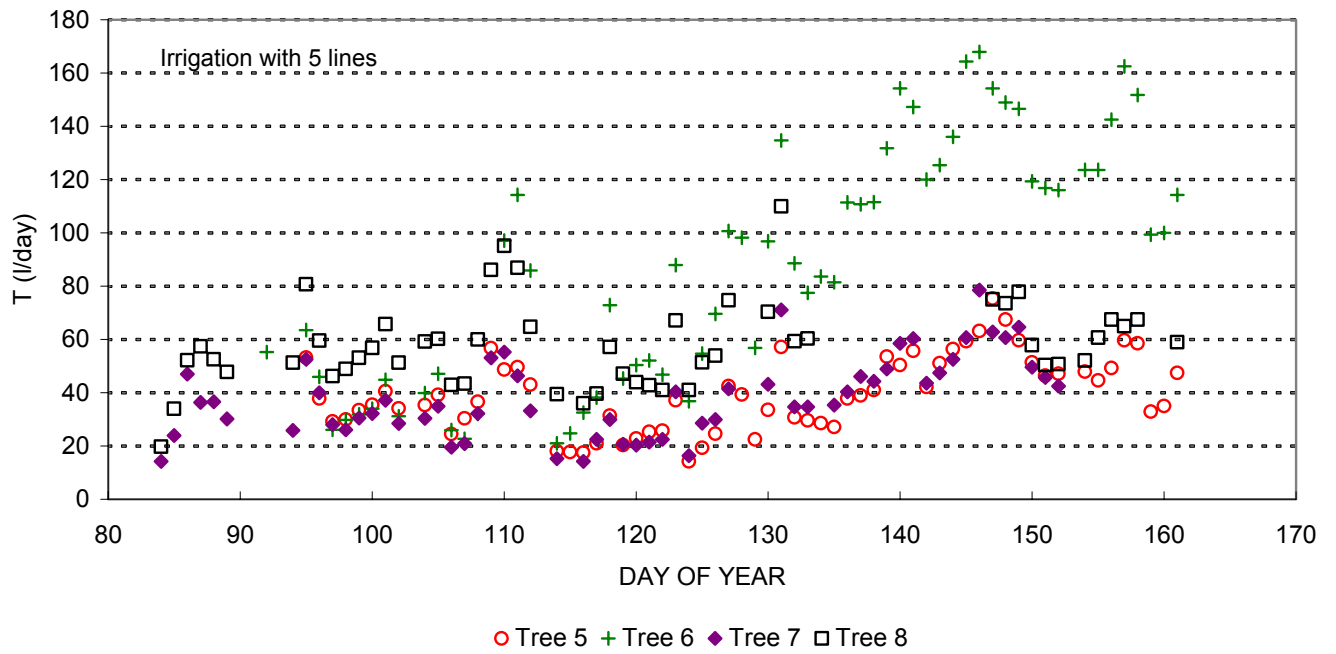
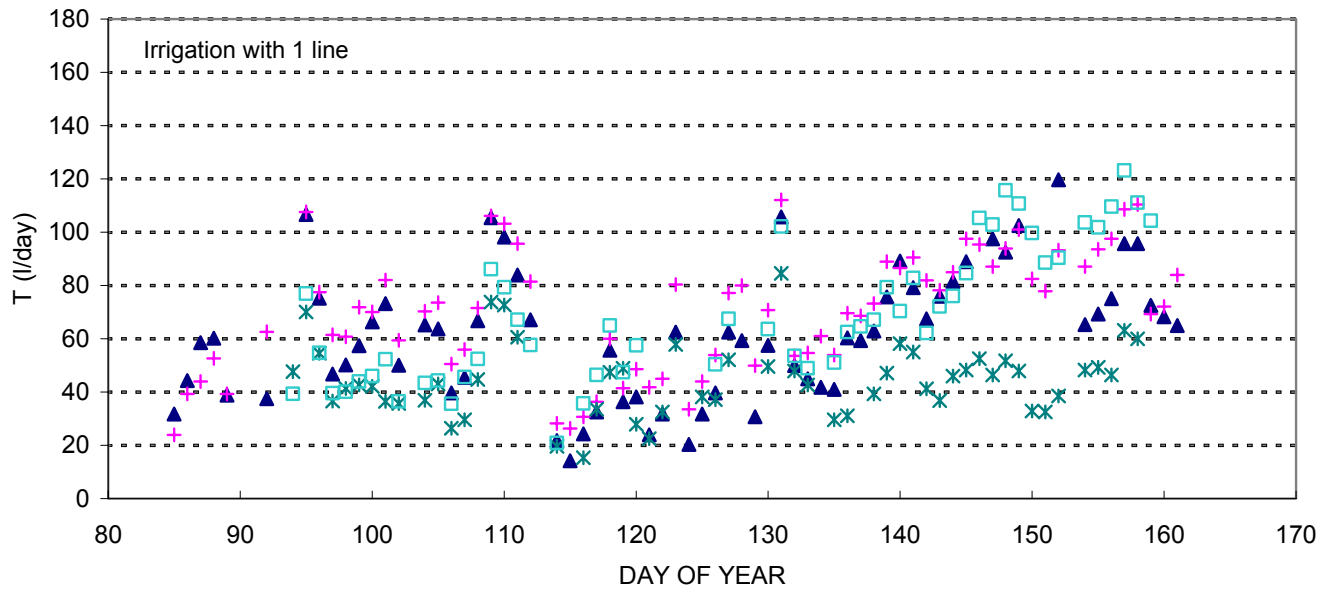


Figure 15



4.6. Transpiration response to the irrigation interval

Variation of daily transpiration was monitored during the interval between irrigations in the five-line treatment. **Figures 16 and 17** show the variation of the ratio between daily transpiration and potential transpiration (T/T_p) and that of potential transpiration (T_p) during four irrigation intervals in September-October 1993 (Fig. 16 a, b, c, d) and four irrigation intervals in April-May 1994 (Fig. 17 a, b, c, d).

In the first two intervals monitored in September 1993 (Fig. 16 a, b) the T/T_p ratio increased to a maximum of 0.18-0.20, measured 3 days after the irrigation. The ratio then decreased to a minimum, recorded 6 days after irrigation. A similar reduction in T/T_p with time after irrigation was observed also during two intervals in October 1993 (Fig. 16 c, d). In both cases, the maximum T/T_p was recorded 2 or 3 days after irrigation, and the minimum T/T_p occurred 6 days after irrigation.

The declining trend of T/T_p during the irrigation interval was also observed at the beginning of the second irrigation season (Fig. 17). T/T_p began to decline 4 days after the irrigation and reached minimum values 6 days after irrigation. This reduction of T/T_p occurred even under conditions of increasing T_p (Fig. 17a, c) that promote water loss from the canopy. The gradual reduction of T/T_p observed towards the end of the irrigation interval confirms that the irrigation frequency used in this treatment caused a reduction of tree hydraulic conductivity and a deterioration of tree water status, starting from 4 days after the irrigation. This unexpected effect was taken into account in the analysis of the tree water status measurements collected in this treatment.

Figure 16

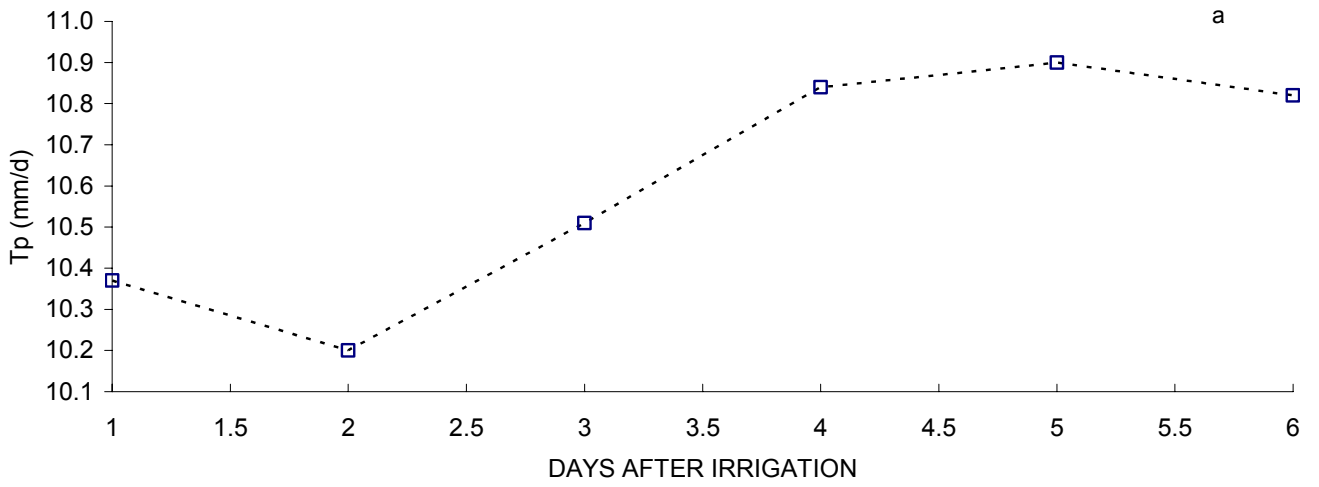
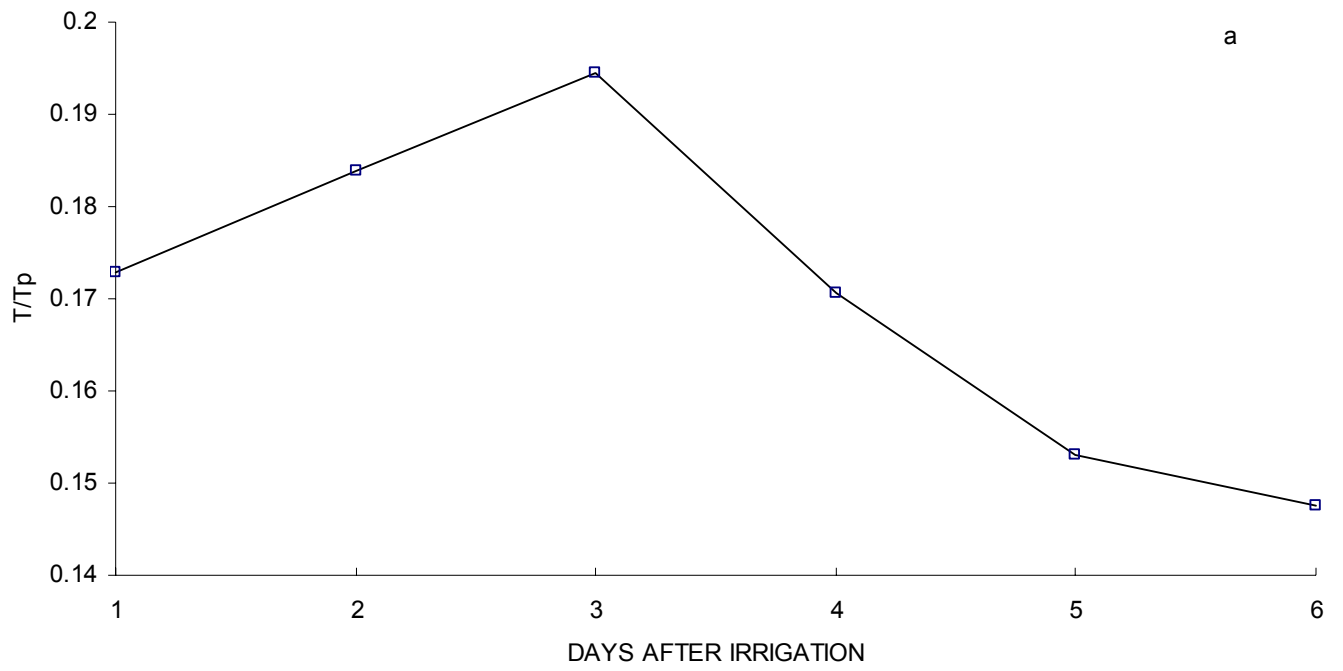


Figure 16b

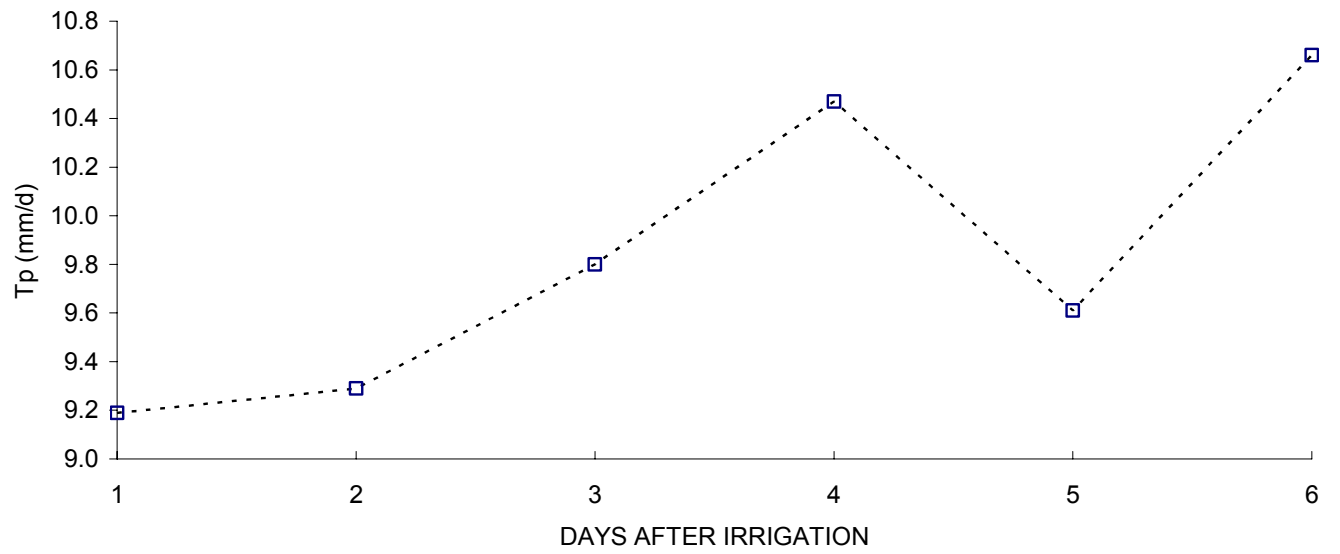
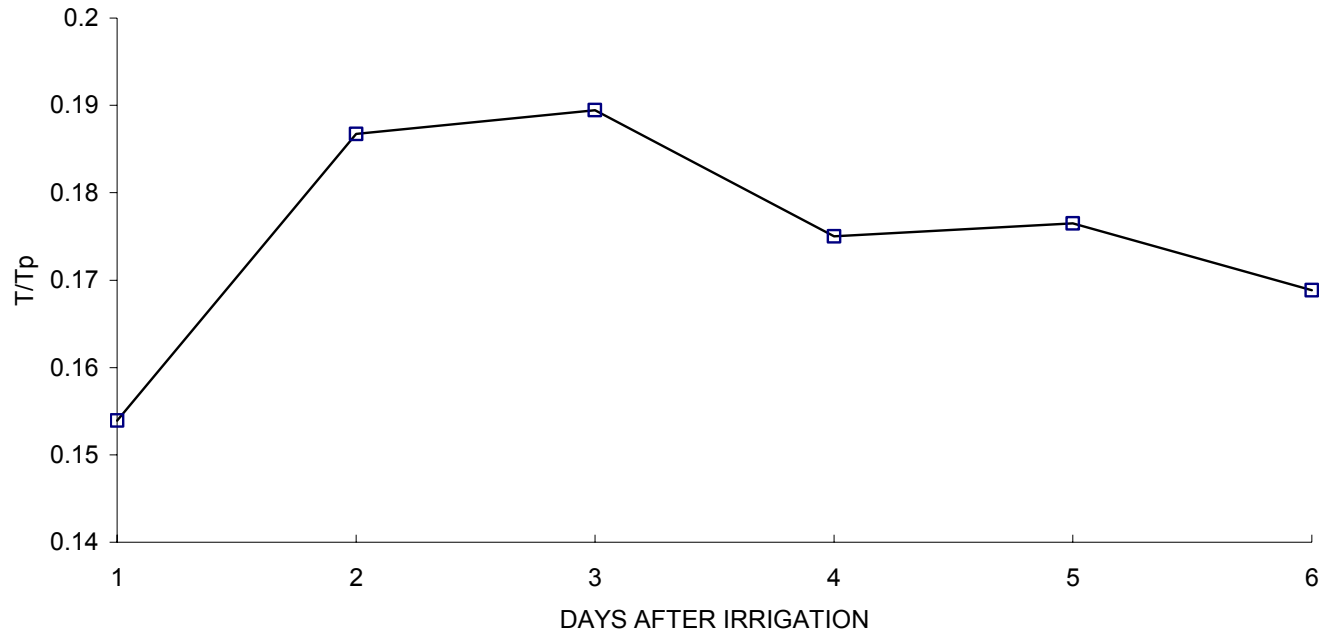


Figure 16c

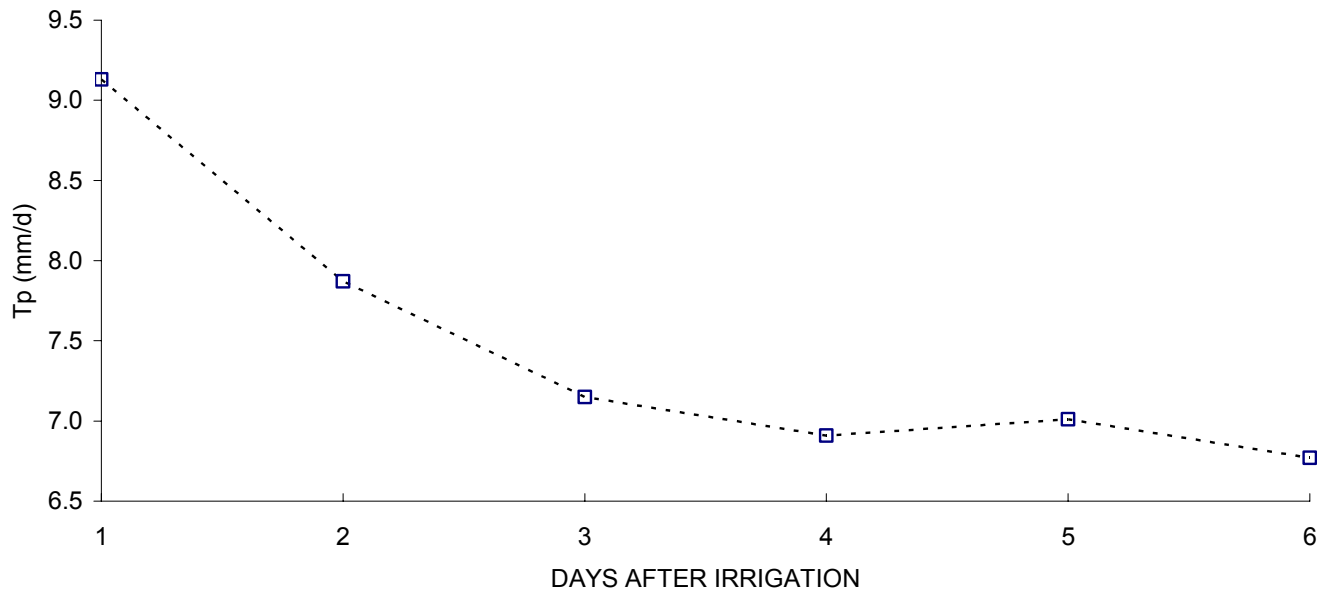
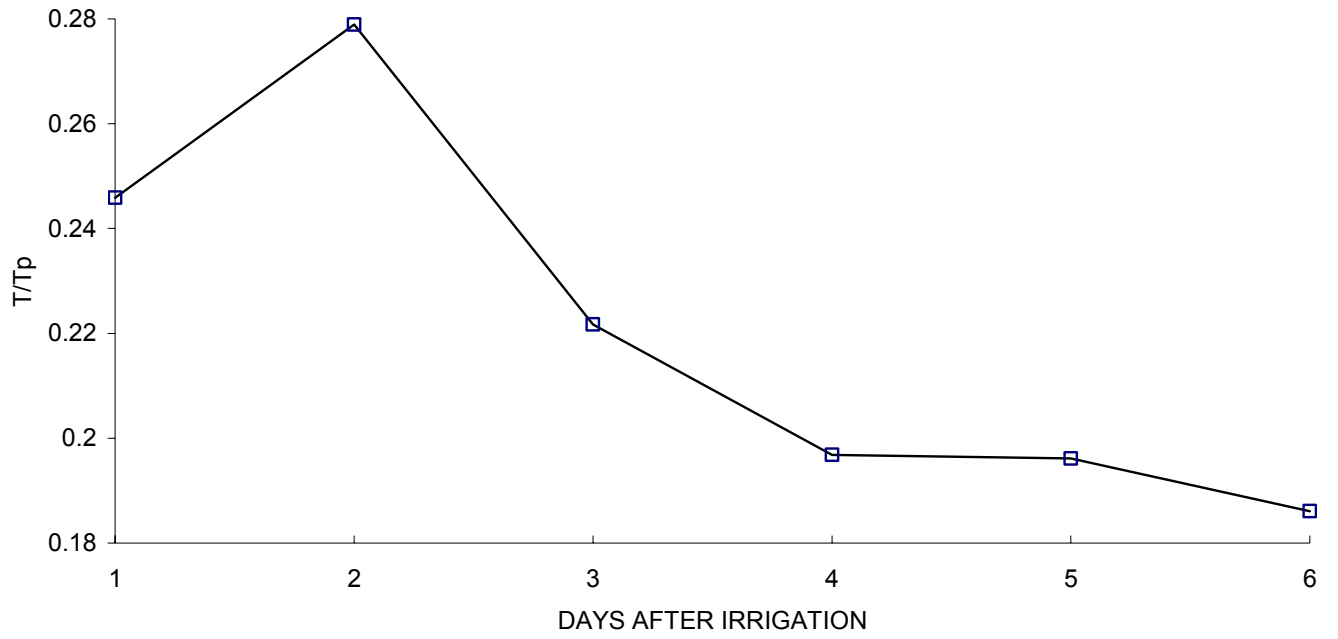


Figure 17a

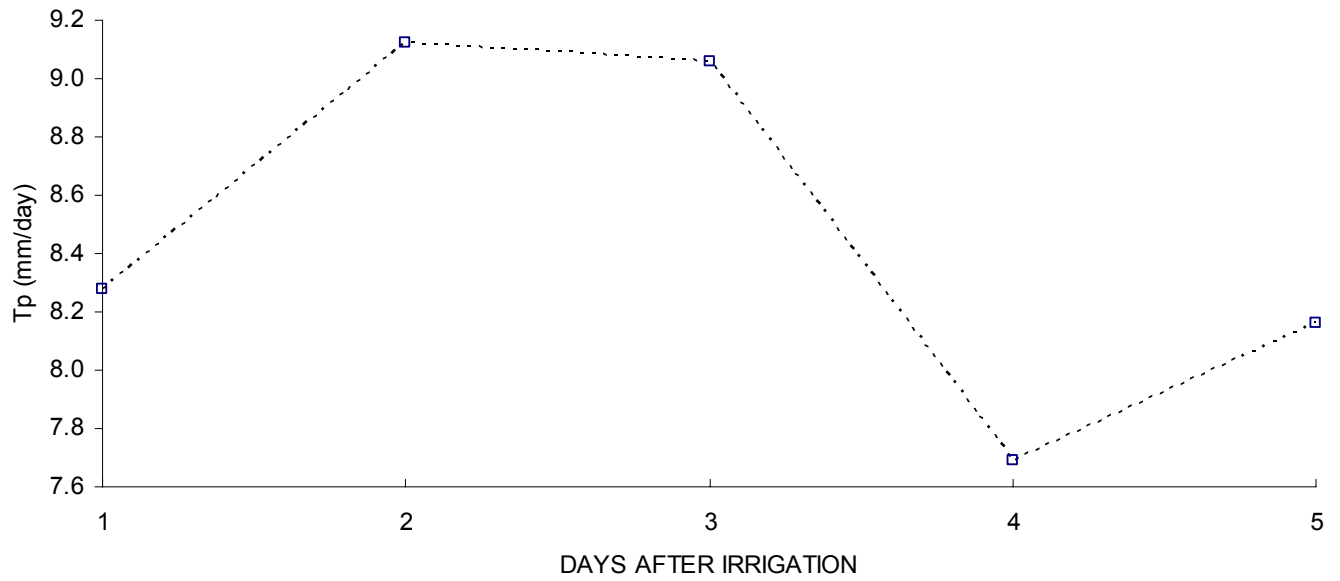
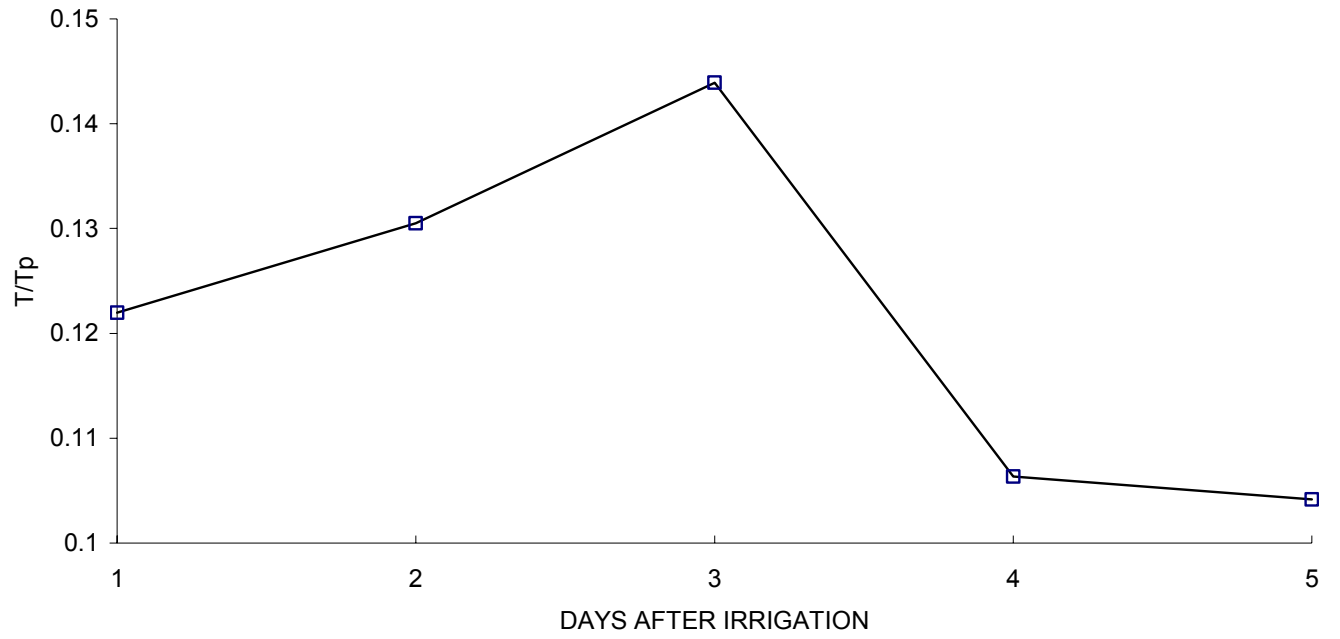


Figure 17b

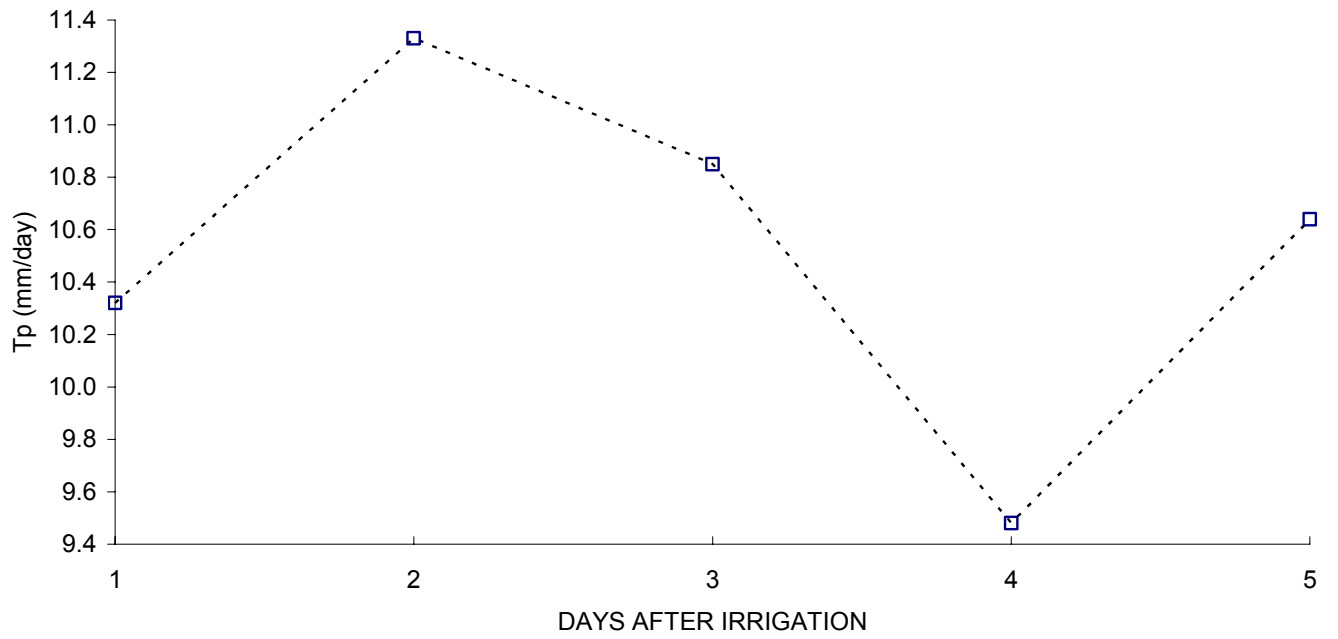
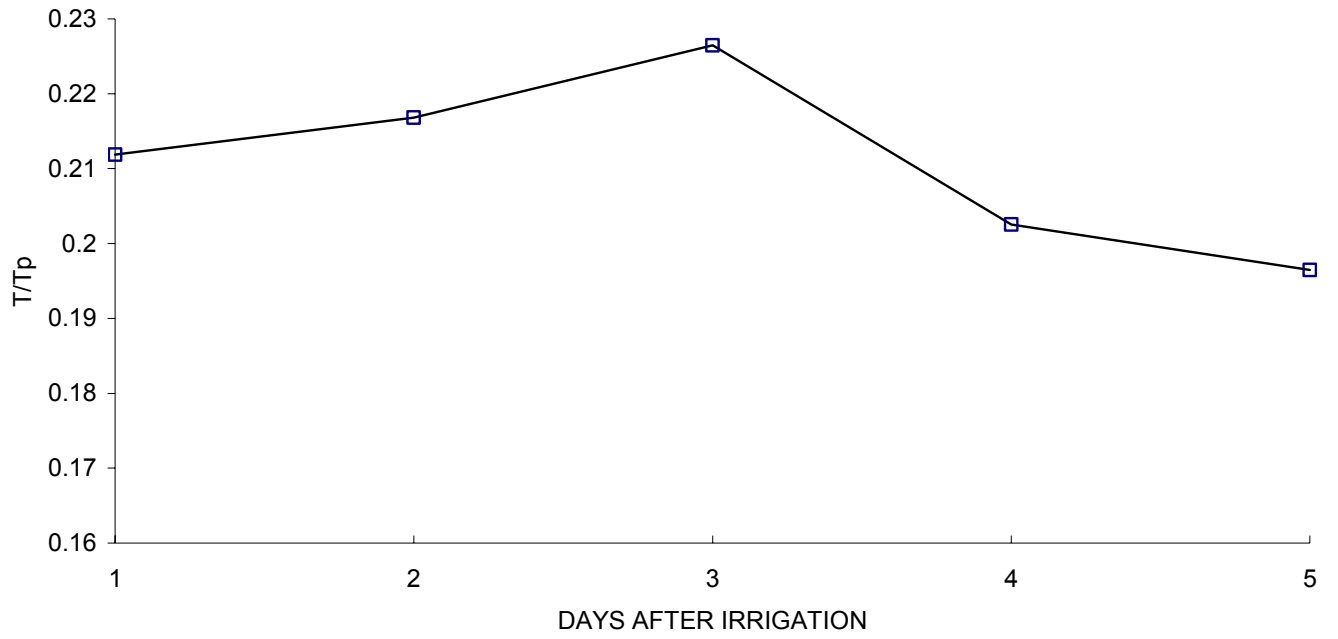
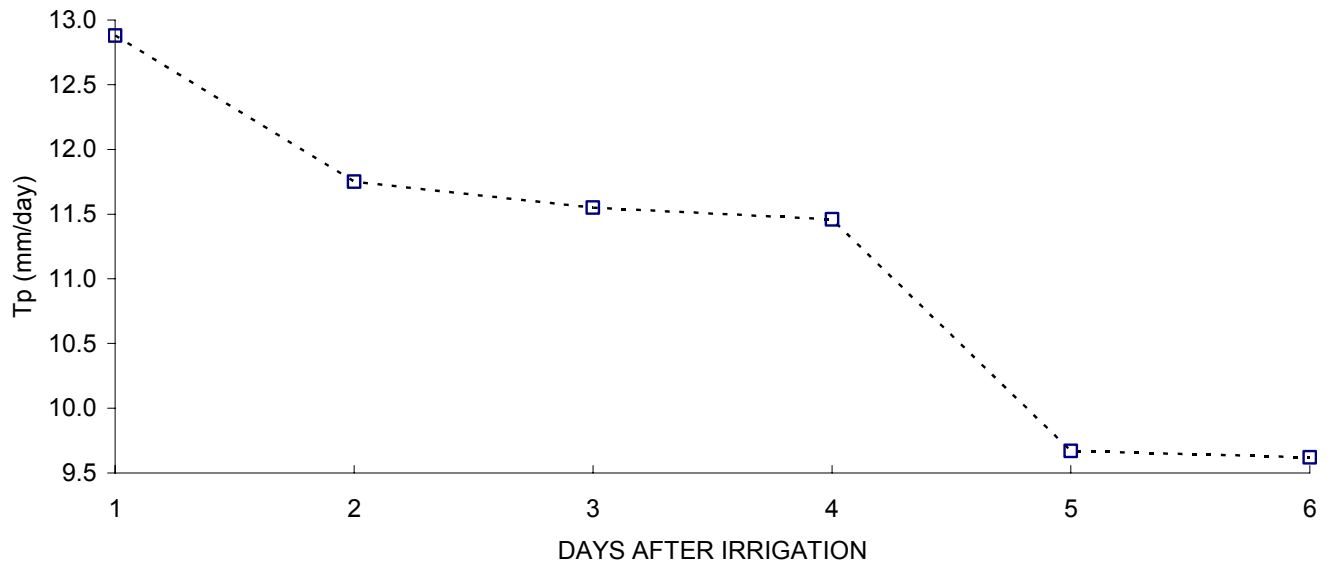
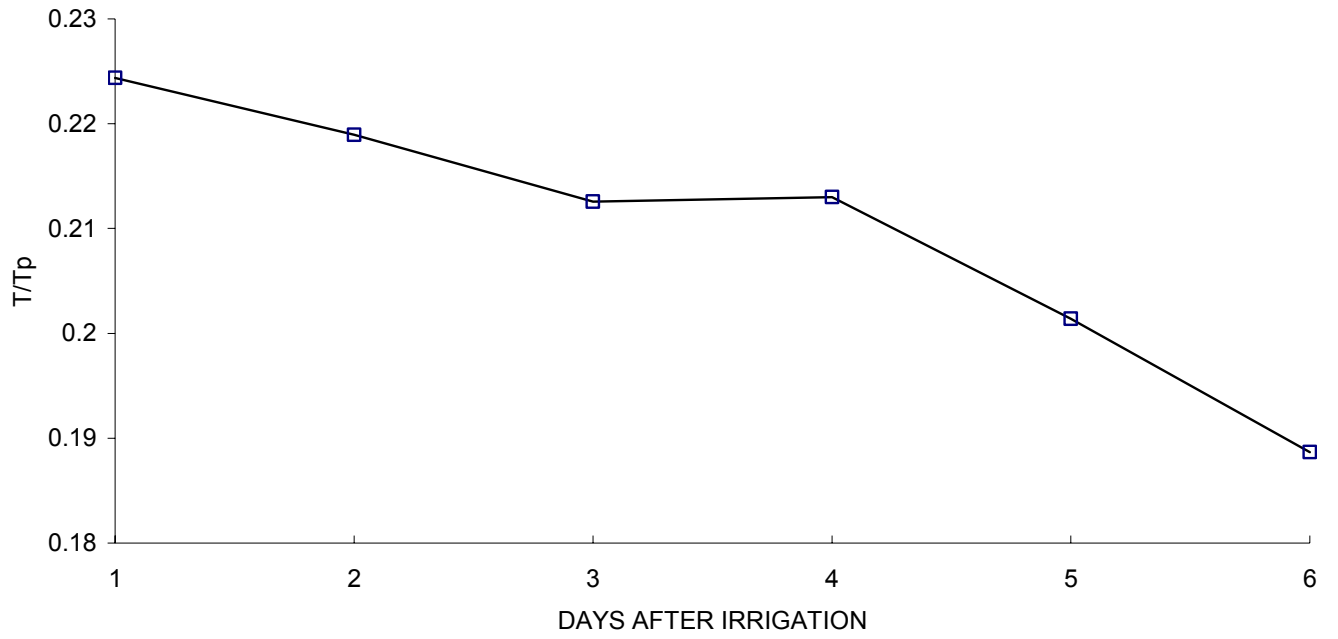


Figure 17c



4.7. Transpiration response to climatic conditions

Periods of high temperatures accompanied by low relative air humidity during the flowering and fruit set period have been reported as detrimental for avocado yield. **Figure 18** shows the course of (a) air temperature and relative humidity, (b) solar radiation and wind speed, and (c) potential transpiration, recorded on a day with extremely hot weather in April 1994 (DOY 110). Daily T_p was 14.6 mm day⁻¹, and air temperature and relative humidity were around 42°C and 27%, respectively, at noon (Fig. 18a).

The relationship between transpiration (T) and potential transpiration (T_p) was studied under non-limiting soil water supply (**Figure 19**). Transpiration data correspond to average hourly measurements collected from four trees in the five-line irrigation treatment in August 1993 (DOY 228), when average soil water contents at 1 m from the trunk were 26.8, 27.5 and 28.2% at 0.25, 0.55 and 0.85 m depth, respectively. A linear relationship was found between T and T_p , suggesting that seasonal variations in avocado transpiration are explained by corresponding variations in the level of evaporative demand.

Figure 18a

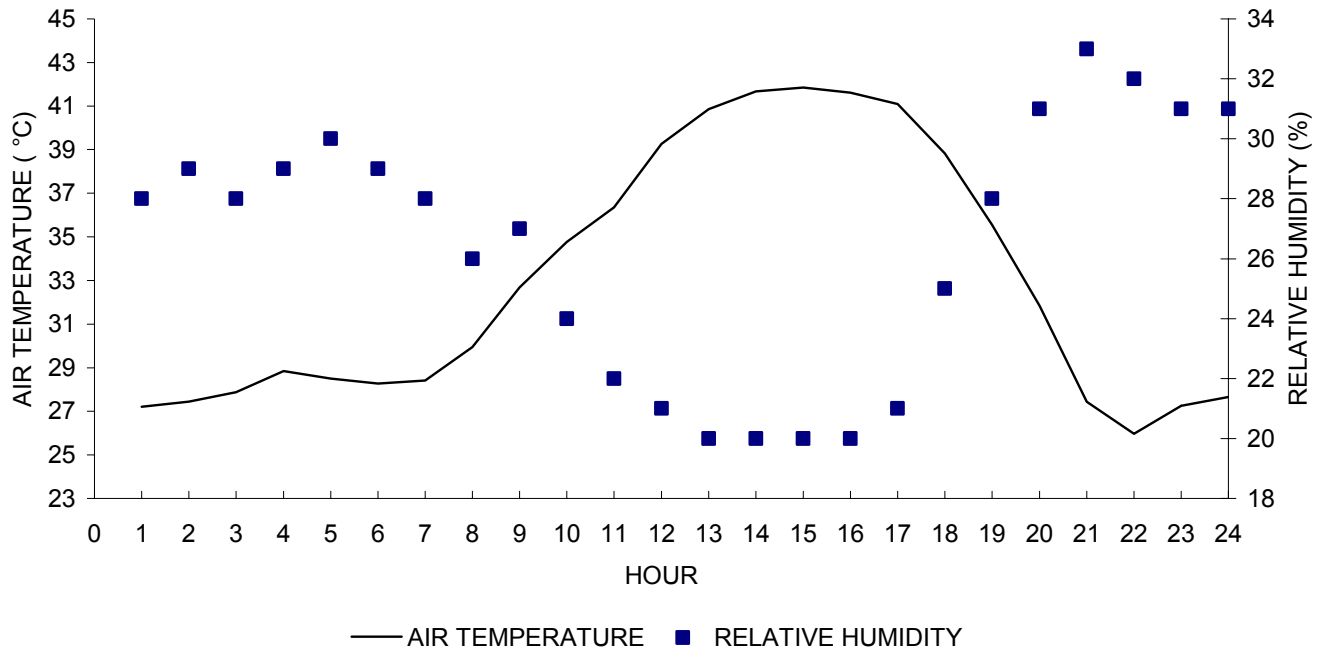


Figure 18b

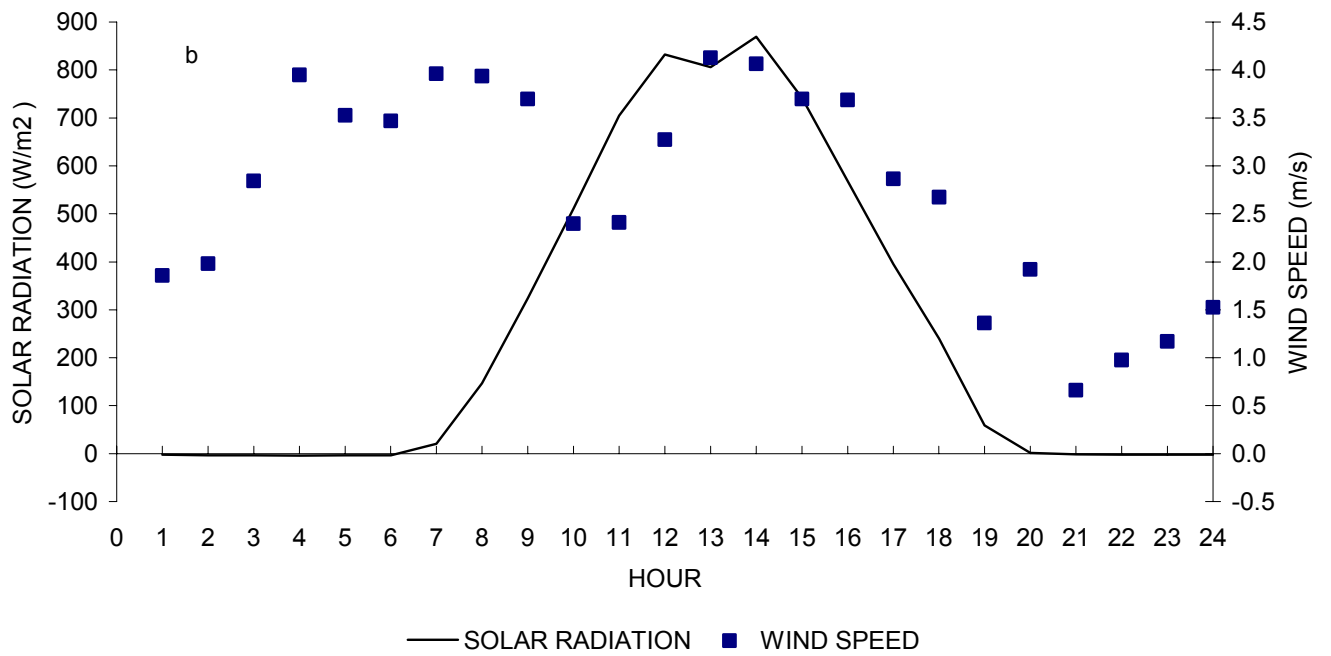


Figure 18c

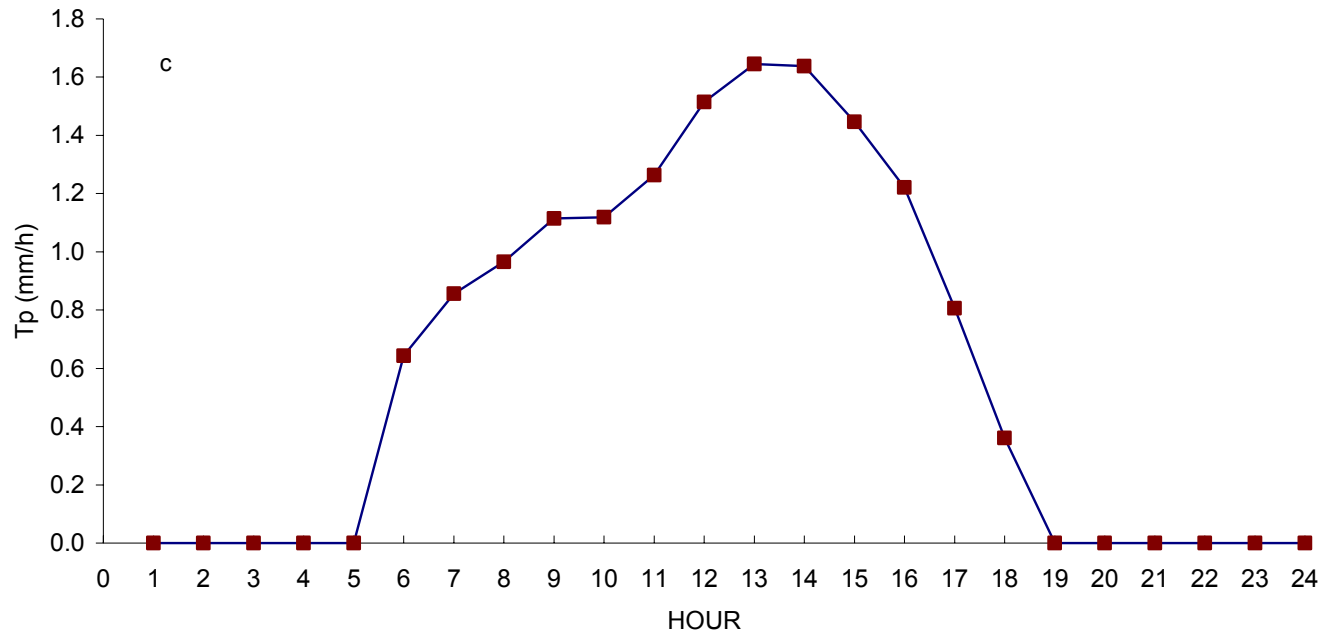


Figure 19

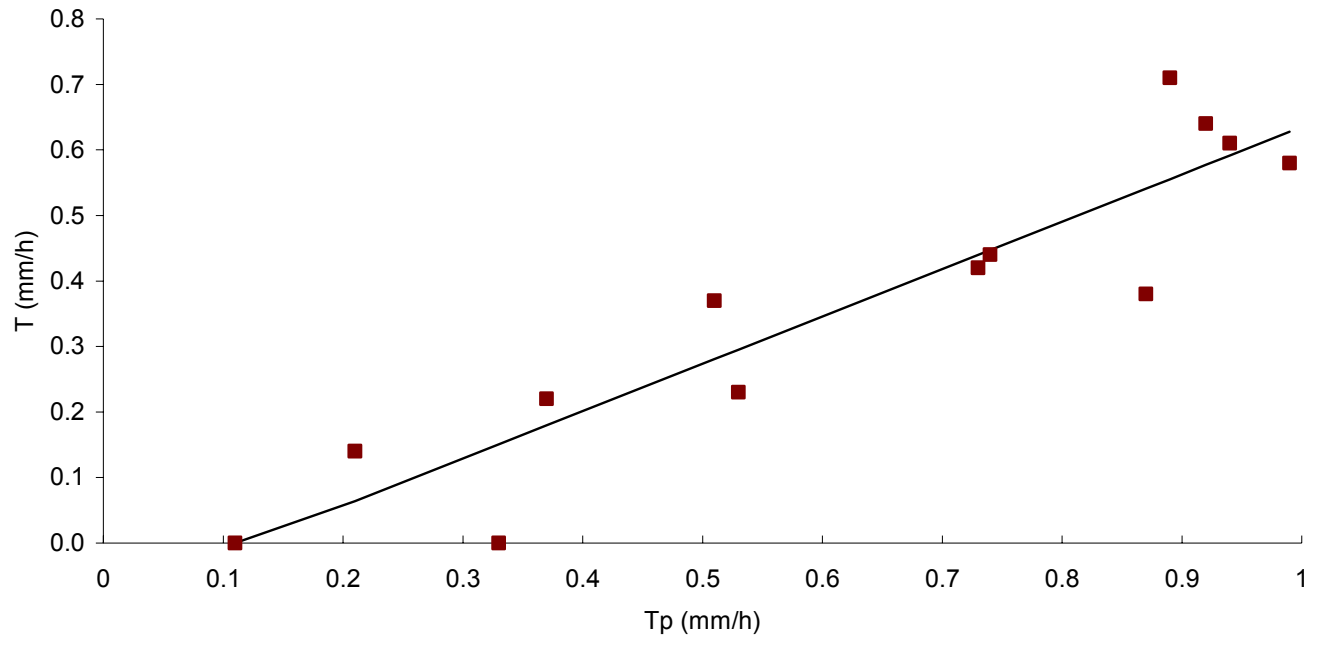


Figure 20 shows the diurnal course of T for both irrigation treatments measured on two days with different T_p : (a) May 22, 1994 ($T_p = 9.48 \text{ mm day}^{-1}$); (b) May 27, 1994 ($T_p = 11.75 \text{ mm day}^{-1}$). Data correspond to average T data collected on three trees per treatment. On both days and for both treatments soil water availability was unrestricted. Maximum differences in T between the treatments were observed at midday. The treatment irrigated by five lines showed higher daily T than the treatment irrigated by one line, on both dates.

On the day with lowest T_p (Fig. 20a), the difference in daily T between the two treatments was smaller than on the day with high T_p (Fig. 20b). The computed daily T/T_p ratios for this day were 0.20 and 0.18 for the five- and one-line treatments, respectively (Fig. 20a). Under high evaporative demand (Fig. 20b) the ratios changed to 0.23 and 0.19, respectively. These results indicate that when water demand is high, avocado trees irrigated by five lines are capable of increasing their transpiration more than the trees irrigated by a single line.

Figure 21 presents the daily variation of T for both irrigation treatments measured on (a) April 15, 1994 ($T_p = 9.06 \text{ mm day}^{-1}$) and (b) April 20, 1994 ($T_p = 14.59 \text{ mm day}^{-1}$), under conditions of unlimited soil water availability for both irrigation treatments. Data correspond to measurements on one tree per treatment. On the day with lowest T_p (Fig. 21a), T/T_p was 0.19 and 0.18 for the treatment irrigated by the five-line and the single-line treatment. On the day with highest T_p (Fig. 21b), the ratio increased to 0.26 for the five-lines treatment, compared with only 0.21 for the single-line treatment. These results indicate that even under high evaporative demand conditions, the tree irrigated by five lines showed a larger increase in T than the trees irrigated by one line. It is suggested that the larger increment in T was due to a larger increase in water uptake by the trees under five-line irrigation, in response to high atmospheric evaporative demands, as a consequence of the enlarged wetted soil area, which modified the root distribution.

Figure 20

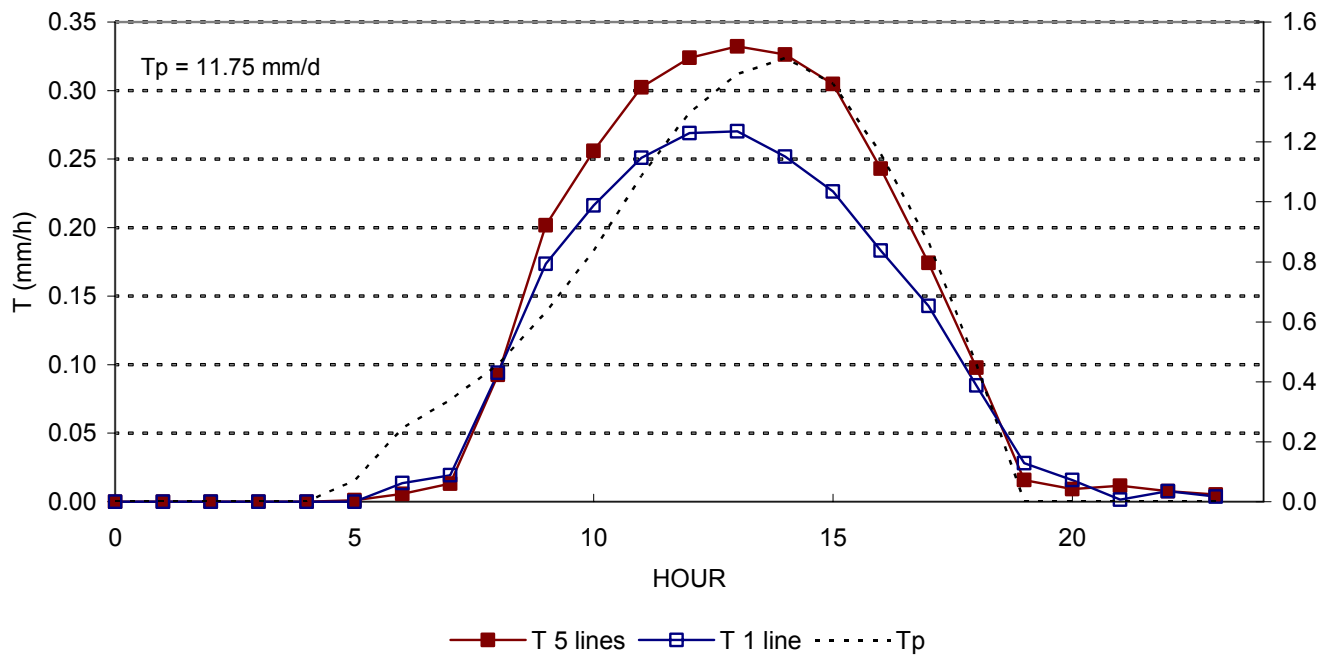
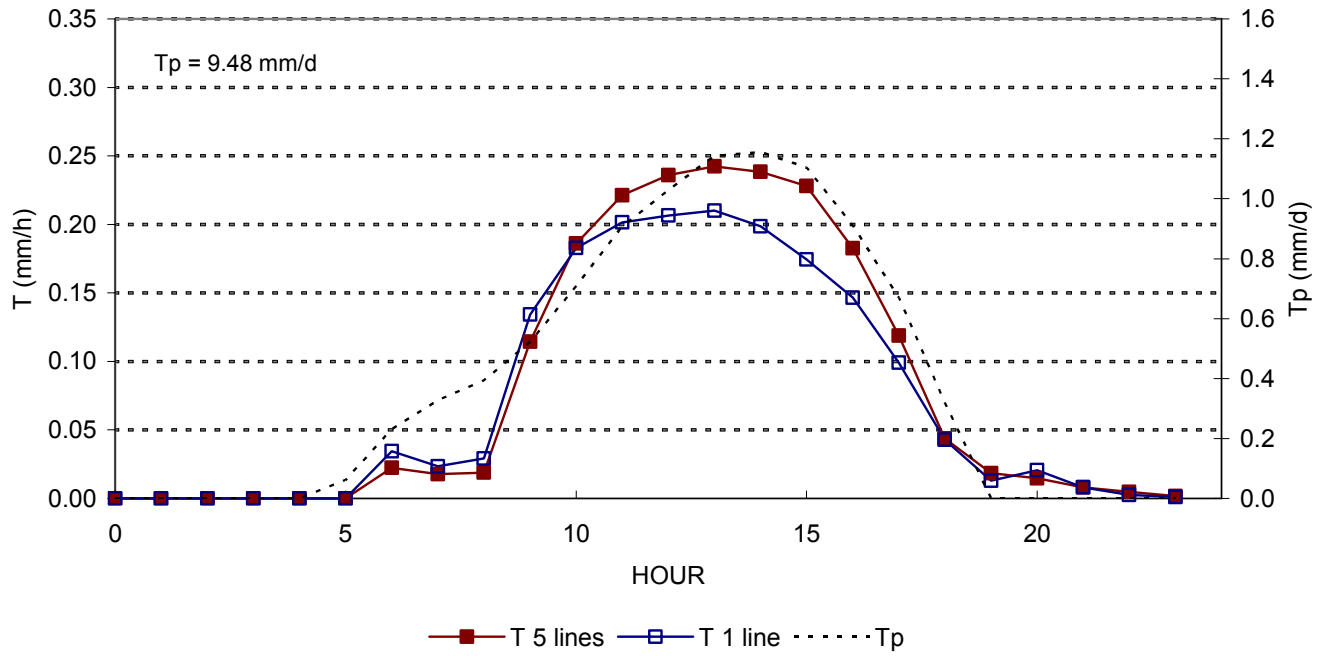
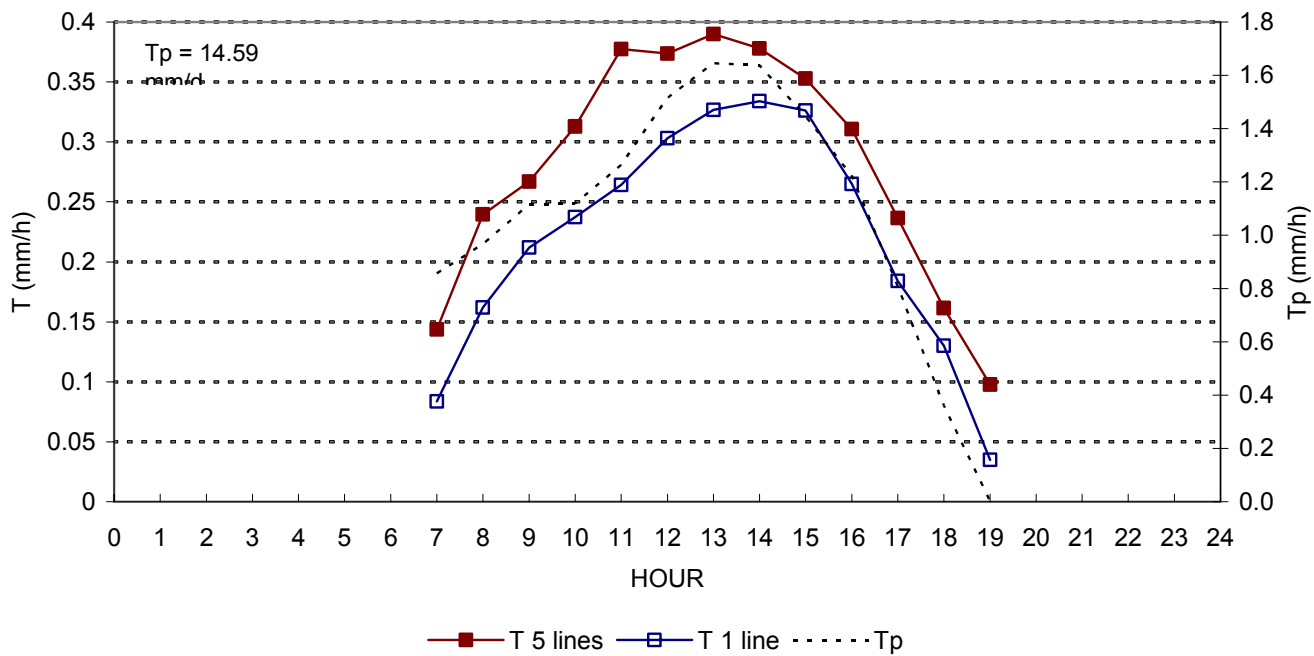
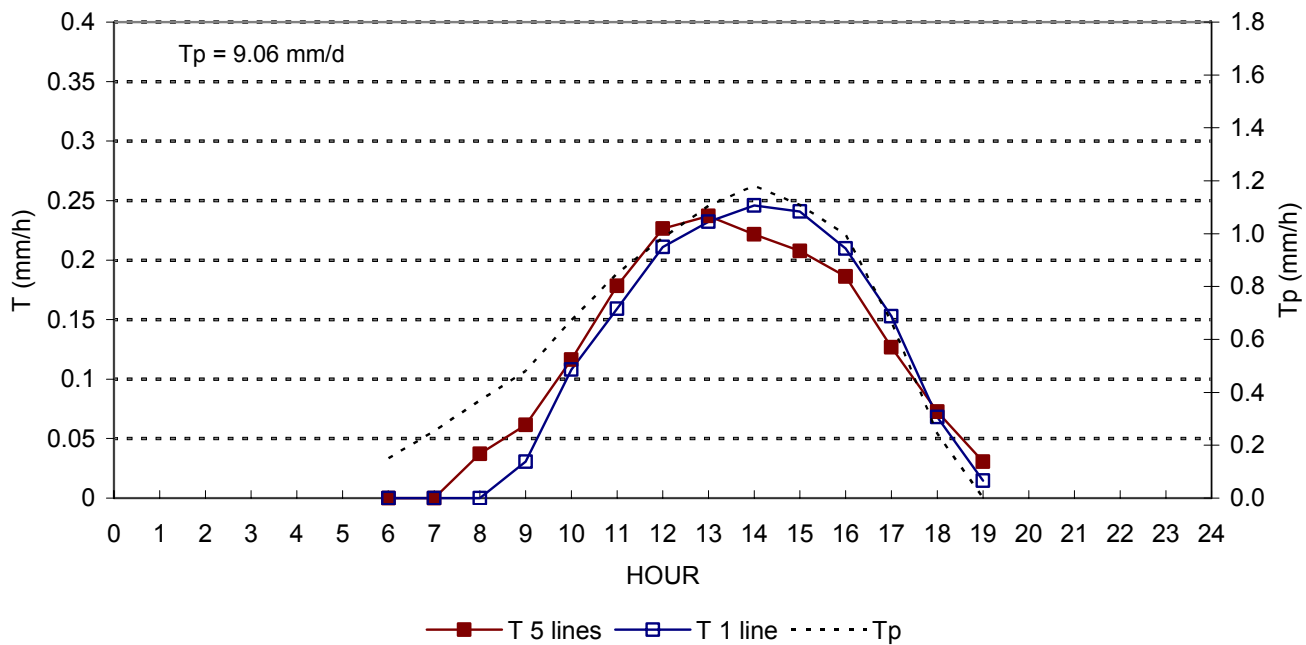


Figure 21



4.8. Change in avocado canopy conductance with potential transpiration

The response of avocado canopy conductance to increasing Tp was studied in both irrigation treatments by monitoring variations of the T/Tp ratio during periods when the treatments were irrigated daily. This practice allowed the maintenance of unlimited water availability in the soil. **Figure 22** presents the relationship between the T/Tp ratio and Tp , as monitored during a period of 11 days in May 1994. Data shown were obtained from individual T measurements collected on four trees per treatment.

In both treatments, T/Tp increased with increasing Tp in most of the trees, except on tree no. 3 in the one-line treatment. These results indicated that under non-limiting soil water availability, transpiration of avocado trees increased at a higher relative rate than Tp . This response of the tree determines the need for a high potential water uptake by the roots, in order to maintain favorable tree water status under high atmospheric evaporative demand.

Analysis of the slopes of the individual curves for all trees in each treatment indicated a large variability of transpiration between trees. No significant differences in mean slope value were found between the treatments. These results indicate that the response of tree transpiration to variations in climatic conditions was no significantly different between trees irrigated by one- or five-dripper lines.

A similar analysis was performed in the flowering period, during periods of high evaporative demand, on days with unrestricted soil water availability in both treatments. **Figure 23** shows the relationship between T/Tp and Tp observed in both treatments at the beginning of April 1994, in the anthesis peak. Data presented in the figure were obtained from individual T measurements collected on four trees per treatment. In both irrigation treatments, the T/Tp ratio increased linearly with increasing Tp up to approximately 9-10 mm day⁻¹. At higher Tp , the T/Tp ratio remained almost constant and did not respond to further increments in potential transpiration. This response differs from that observed in Fig. 22 (May 1994), when T/Tp still increased with Tp over 10 mm day⁻¹. These results may suggest the effect of factors other than soil water content and climate, that limit the transpiration response of avocado trees to conditions of high Tp during the flowering period.

Figure 22

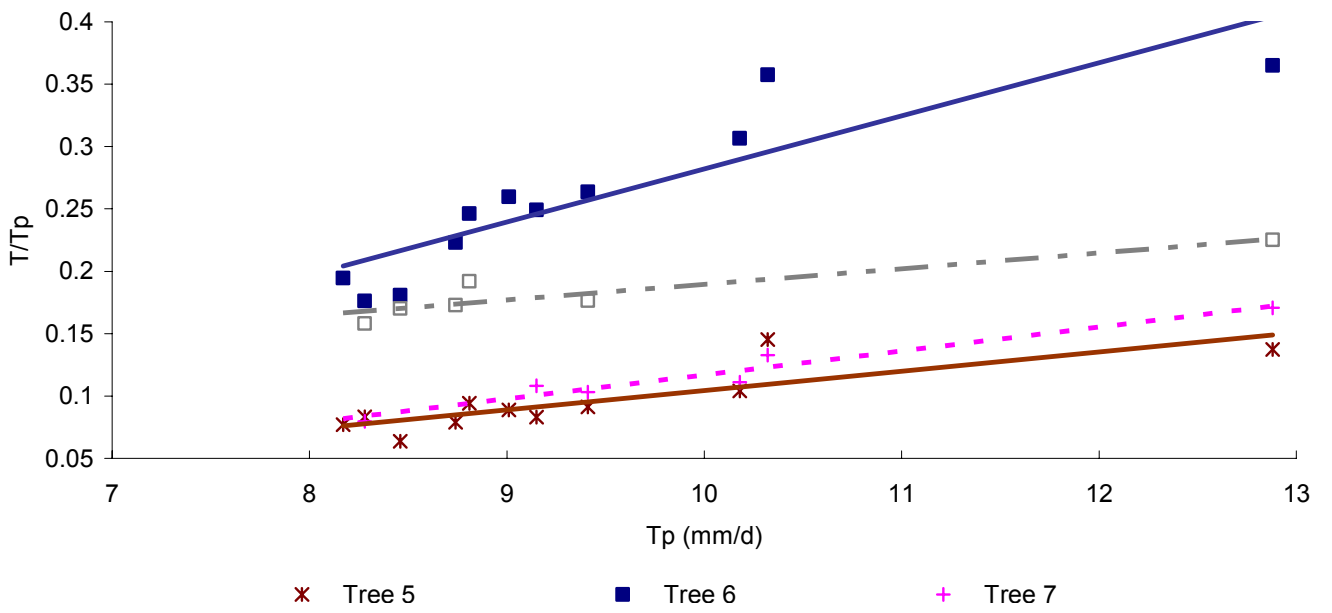
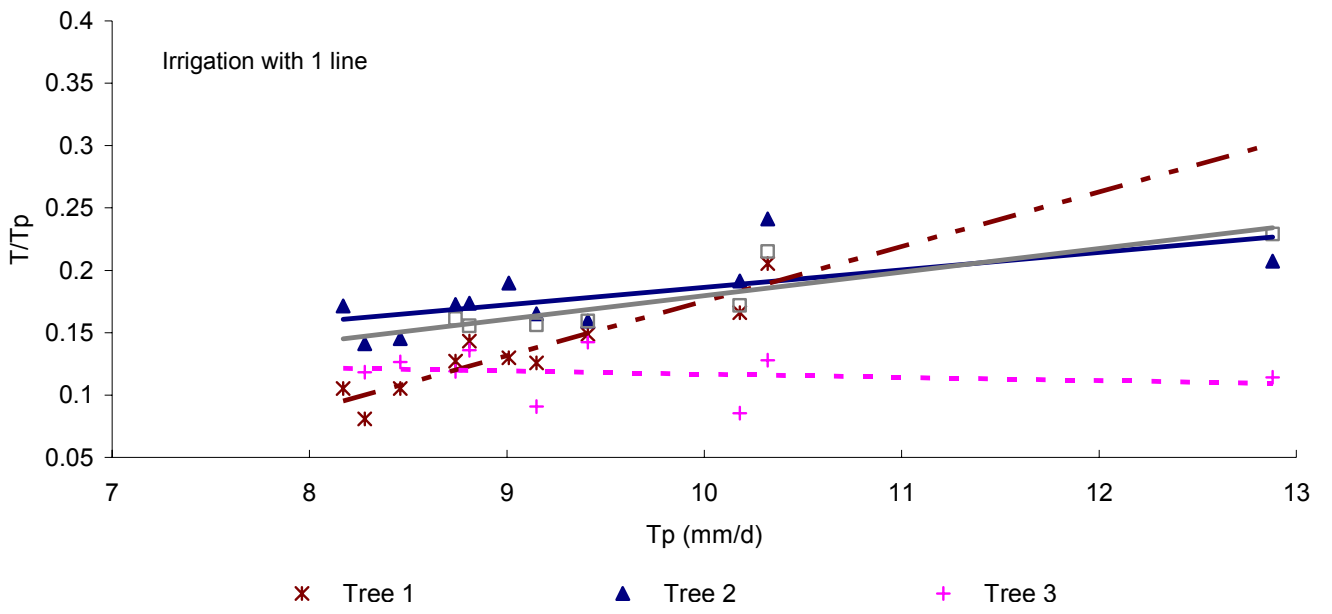
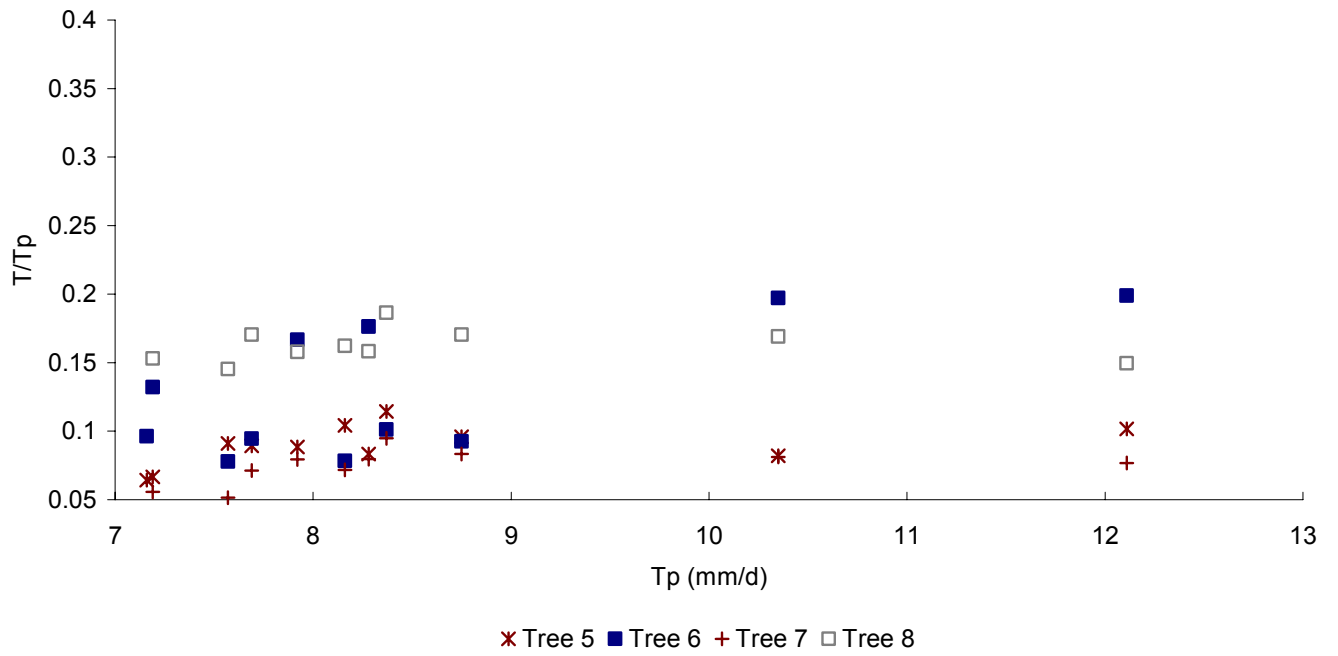
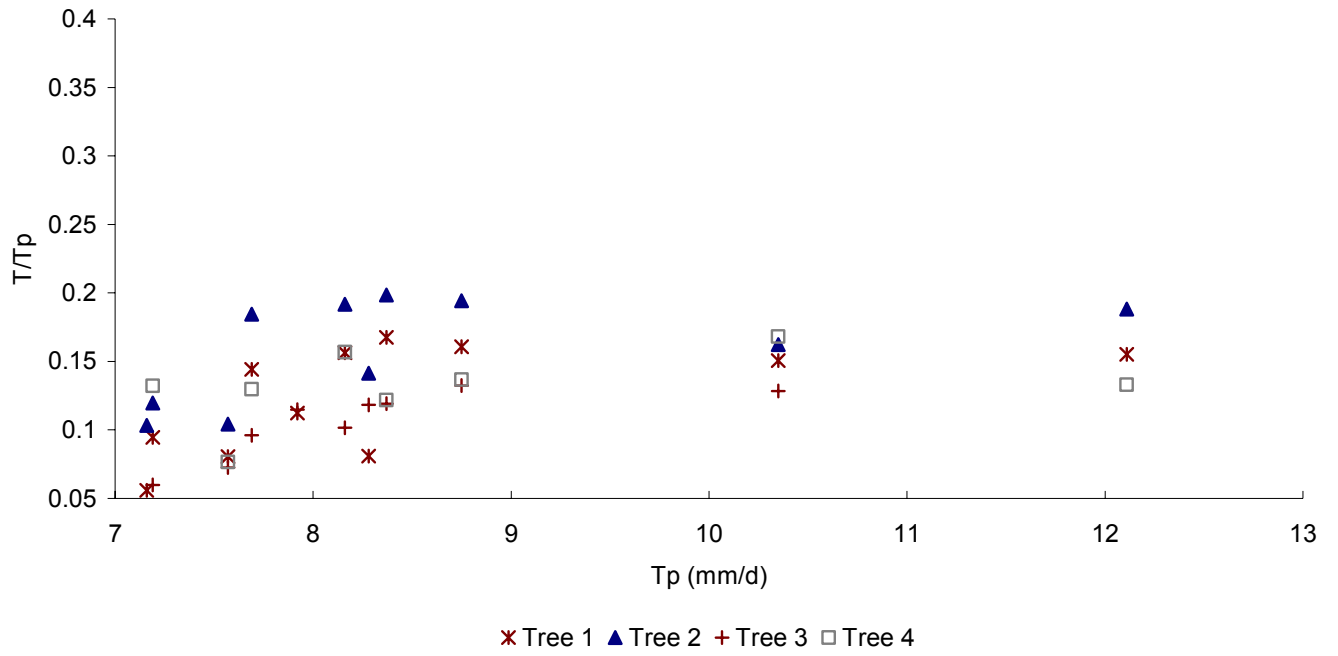


Figure 23



4.9. Effect of the irrigation treatments on canopy water status during the flowering and fruit-set period

Figure 24 shows the variation in leaf xylem water potential (*LWP*, MPa) at noon as a function of daily *T_p*, as measured on sunlit and shaded leaves of both irrigation treatments during April-May 1994. Data presented in the figure were taken on days when the soil was wet in both treatments, to eliminate the effect of soil water availability on xylem potential. *LWP* decreased with increasing *T_p*. Higher water potentials were observed in trees irrigated by five lines than in those irrigated by a single line, for the same *T_p* rate. *LWP* of sunlit leaves was lower than that of for shaded ones; nevertheless, the treatment effect is reflected in both groups of leaves.

Table 3 presents the average *LWP* (MPa) measured for each irrigation treatment during four periods during the morning, on both shaded and sunlit leaves. Data were taken on days with non-limiting soil water availability for both treatments. Higher water potentials were observed in the early morning, decreasing towards noon. The treatment irrigated by five lines showed higher *LWP* than the treatment irrigated by a single line.

TABLE 3. Average values of *LWP* (MPa) measured in each irrigation treatment during four periods in the morning, on shaded and sunlit leaves.

Period (h)	Irrigation treatments			
	<i>Sunlit leaves</i>		<i>Shaded Leaves</i>	
	1 line	5 lines	1 line	5 lines
9:00-10:00	-0.53	-0.44	-0.47	-0.36
10:00-11:00	-0.76	-0.66	-0.49	-0.41
11:00-12:00	-0.73	-0.65	-0.45	-0.41
12:00-13:00	-0.90	-0.72	-0.61	-0.48

Figure 24

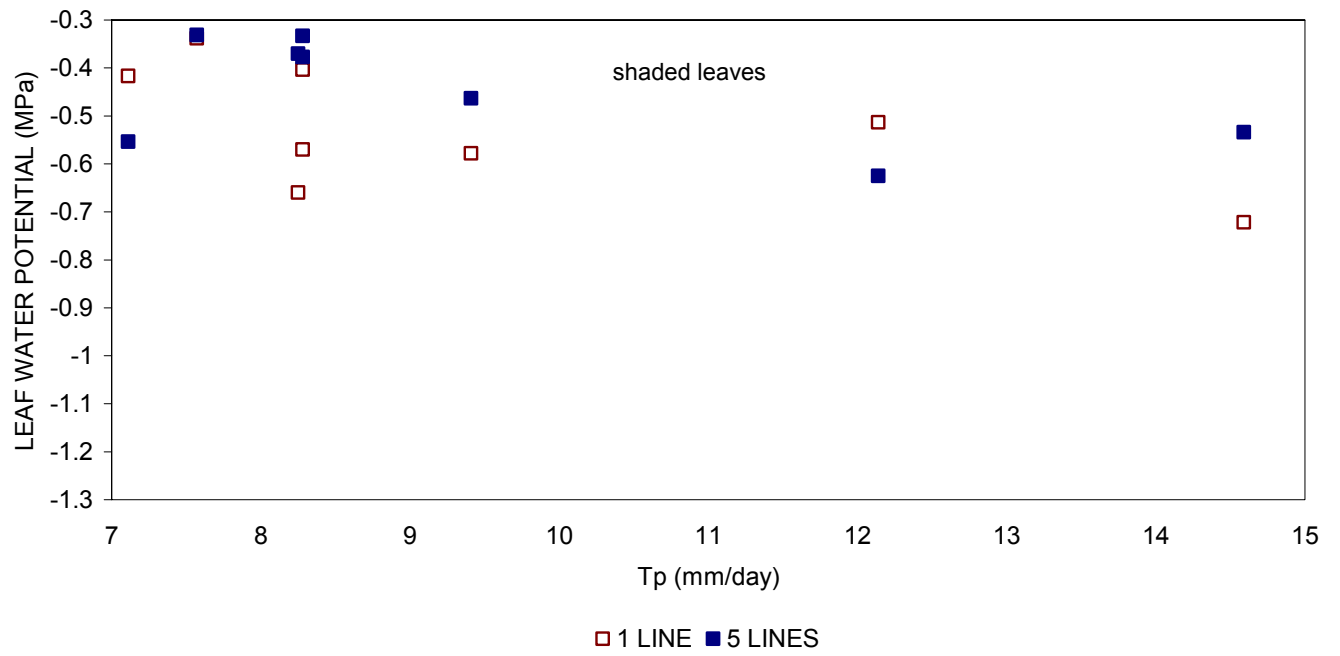
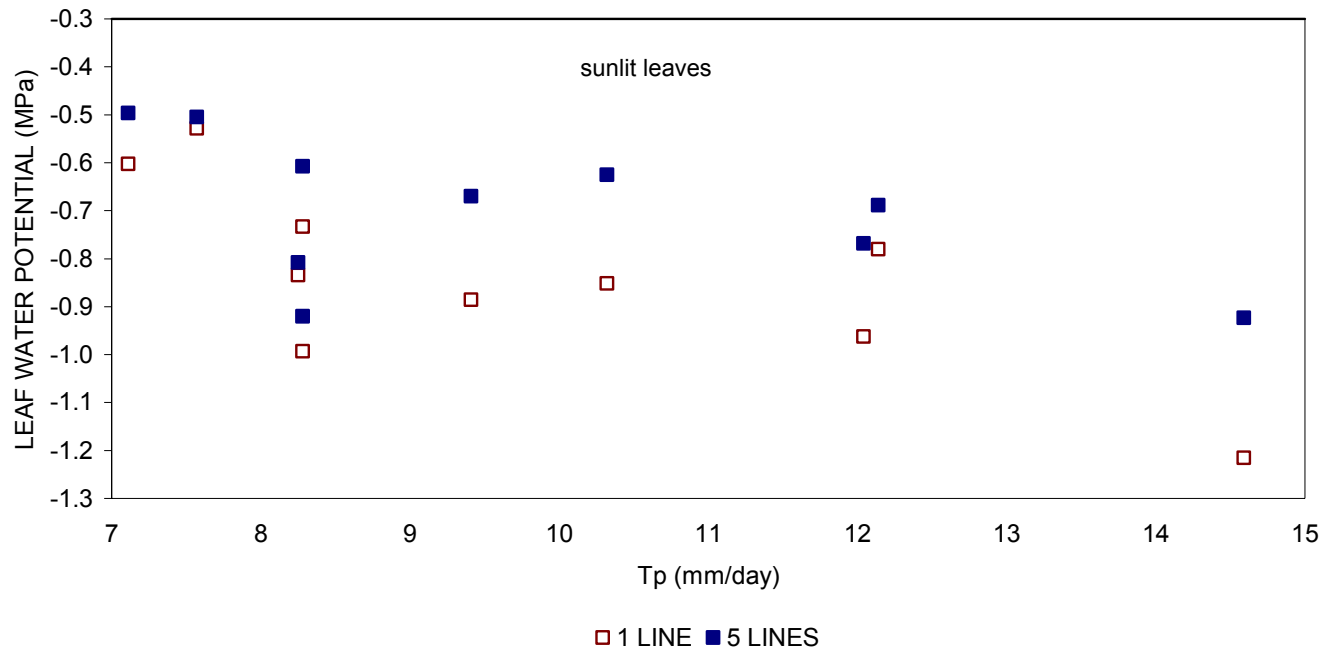
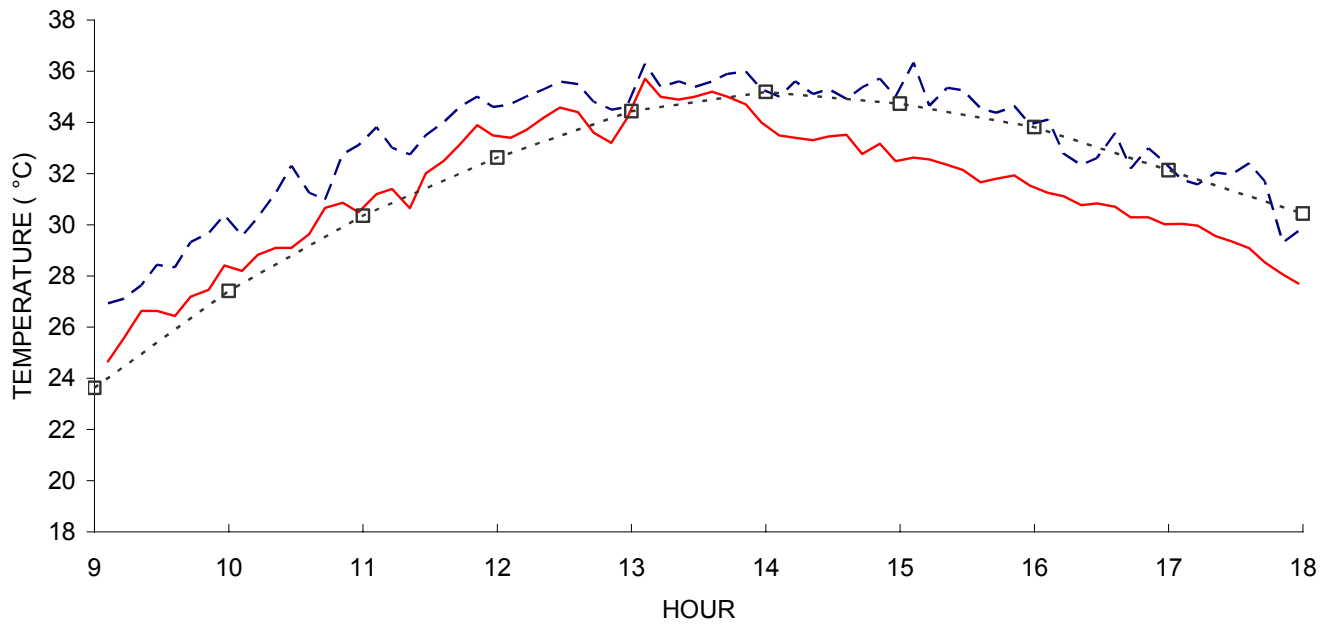
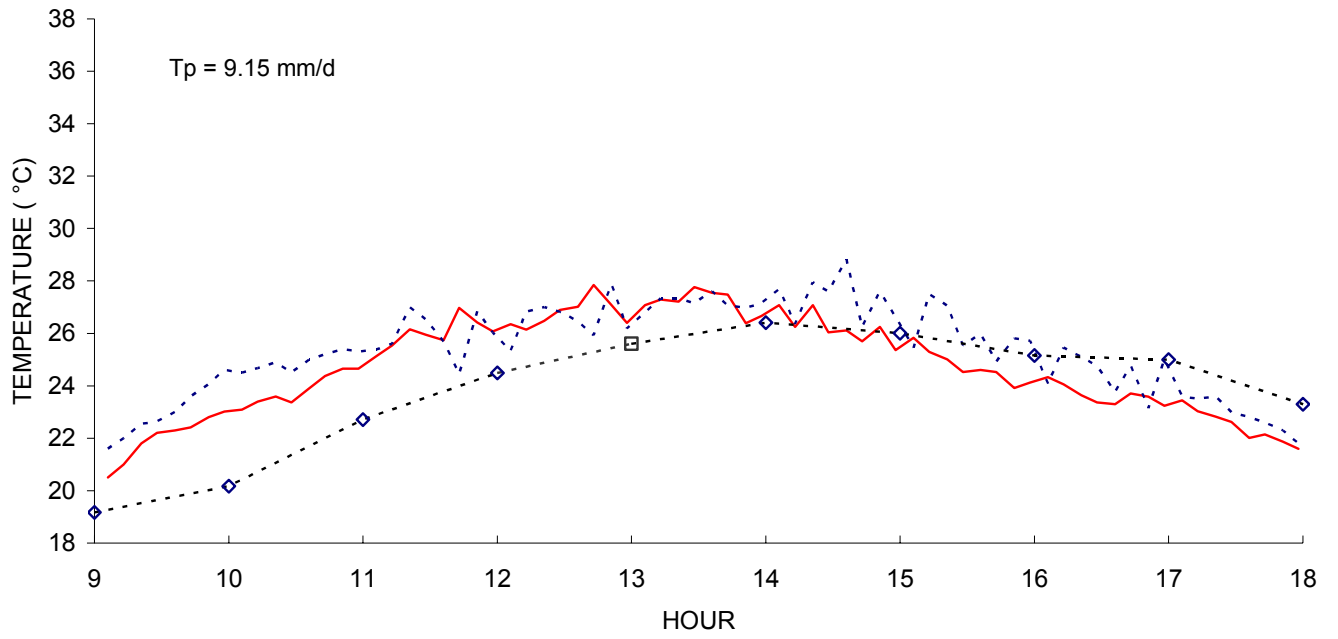


Figure 25 shows a section of the daily course of canopy and air temperature as measured on two days with differing Tp : (a) May 15, 1994 ($Tp = 9.15 \text{ mm day}^{-1}$); (b) May 20, 1994 ($Tp = 11.33 \text{ mm day}^{-1}$). The canopy temperature was measured with fixed-position infrared thermometers on one tree per treatment. On the day with lower Tp , slight differences in canopy temperature were observed between the treatments before midday and in the afternoon, while no differences were found around noon. In the day with higher Tp , air temperature reached 34°C at midday. In the morning, canopy temperature of the single-line treatment was around $1\text{-}3^{\circ}\text{C}$ higher than in the five-lines treatment, but this difference decreased to $1\text{-}2^{\circ}\text{C}$ at noon. In the afternoon, the canopy temperature of the single-line treatment remained 2°C higher than that in the five-line treatment. The lower canopy temperature registered in this treatment in the afternoon is explained by a faster shading of the canopy surface measured by the infrared thermometer on this tree, than that on the tree irrigated with one line, whose canopy remained exposed to the sun for a longer time.

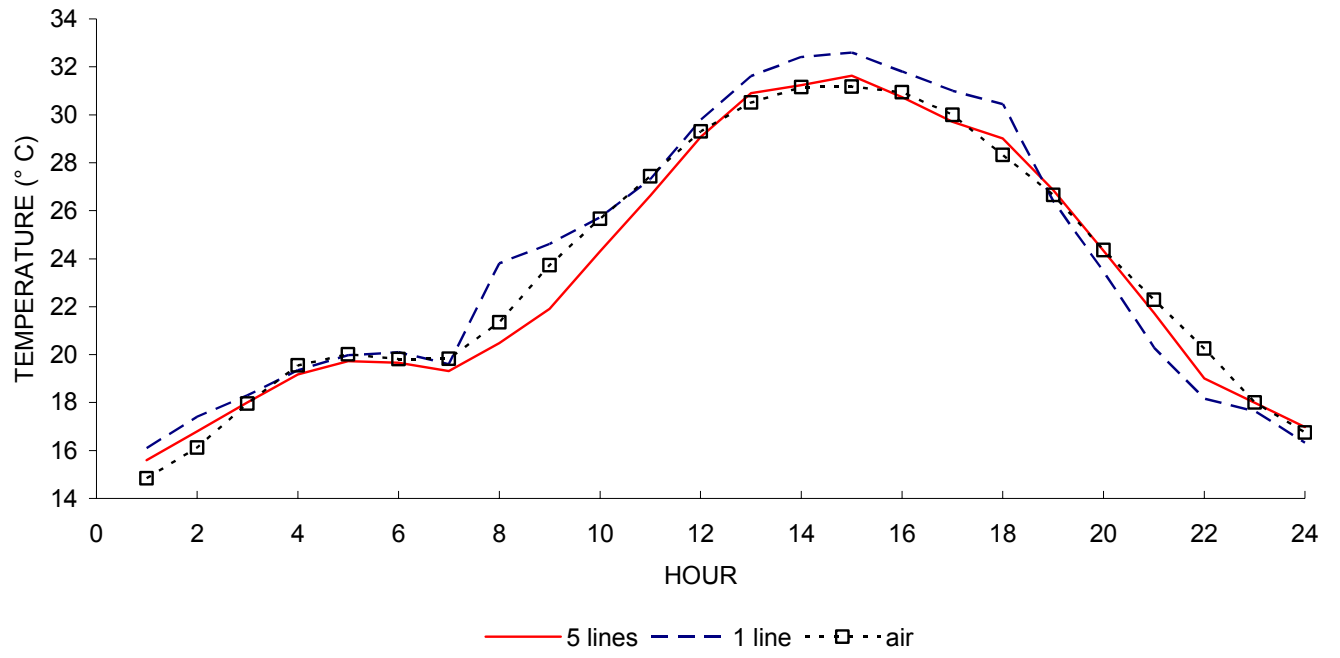
Further evidence of the favorable effect of the five- line irrigation treatment on tree water status is demonstrated in **Figure 26**, that shows the canopy temperature response to the irrigation treatments on a day with non-limiting soil water availability for both treatments (May 30, 1994). At 9:00 h canopy temperature of the tree irrigated by five drip lines was around 1.8°C lower than that of the tree irrigated by one line. This difference decreased to 0.7°C at noon. During the whole daylight period, the canopy temperature of the treatment irrigated by a single dripper line was higher than the air temperature, confirming the development of a more severe water stress, which affected the treatment during those hours.

Figure 25



— 5 LINES — 1 LINE ··· □ ··· AIR

Figure 26



Canopy temperature measurements collected with a hand-held infrared thermometer were utilized to verify the magnitude of the differences between the treatments observed with fixed-position infrared thermometers. **Figure 27** shows the change in the canopy temperature difference between the one-line and five-line treatments ($T_{c1}-T_{c5}$) and the change in canopy temperature of the one-line treatment (T_{c1}), with increasing T_p . Data were collected in April-May 1994, on days with non-limiting soil water supply for both irrigation treatments. The figure shows clear increases in both T_{c1} and $T_{c1}-T_{c5}$ with increasing T_p . At low T_p rates, $T_{c1}-T_{c5}$ remained close to or less than zero. On days with T_p higher than 12 mm day^{-1} , $T_{c1}-T_{c5}$ increased to more than 1°C , indicating the development of a more severe water stress in the canopy of trees irrigated by a single line than in those of the trees irrigated by five lines.

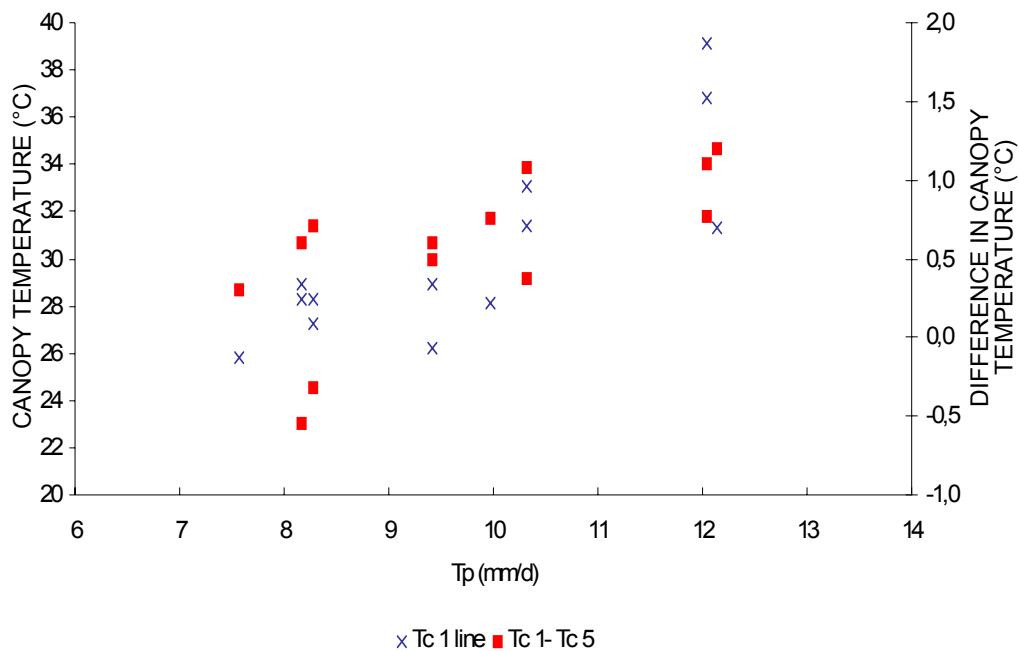


Figure 27. Change in the canopy temperature difference between the one-line and five-line treatment ($T_{c1}-T_{c5}$) and in the canopy temperature of the one-line treatment (T_{c1}) with increasing T_p during April-May 1994. Canopy temperature data were collected with a hand-held infrared thermometer, on days with non-limiting soil water supply in both irrigation treatments.

4.10. Soil-Plant-Atmosphere numerical model

Figure 28 shows the relationship between daily transpiration rate, as estimated by the numerical model (*Modeled T*) and the average transpiration, as measured by means of the heat-pulse technique (*Measured T*) in both irrigation treatments, during April-May 1994. When *T* was expressed in units of liters per tree per day, a good correlation was found between estimated and measured values ($R^2=0.59-0.60$, for the one- and five-lines treatment, respectively). Modeled *T* underestimated measured *T* by around 11% in both treatments. Average values of measured *T* ranged between 29 and 103 l day⁻¹ per tree in the treatment irrigated by five lines, and between 37 and 92 l day⁻¹ per tree in the treatment irrigated by one line. The standard deviation of measured *T* values ranged between 9.8 and 49.2 l day⁻¹ per tree for the treatment irrigated by five lines, compared with 2.4-22.9 l day⁻¹ per tree for the treatment irrigated by one line. Modeled *T* ranged between 36 and 73 l day⁻¹ per tree and between 37 and 72 l day⁻¹ per tree respectively, for the same treatments.

Figure 28. Relationship between modeled *T* and measured *T* for both irrigation treatments during April-May 1994.

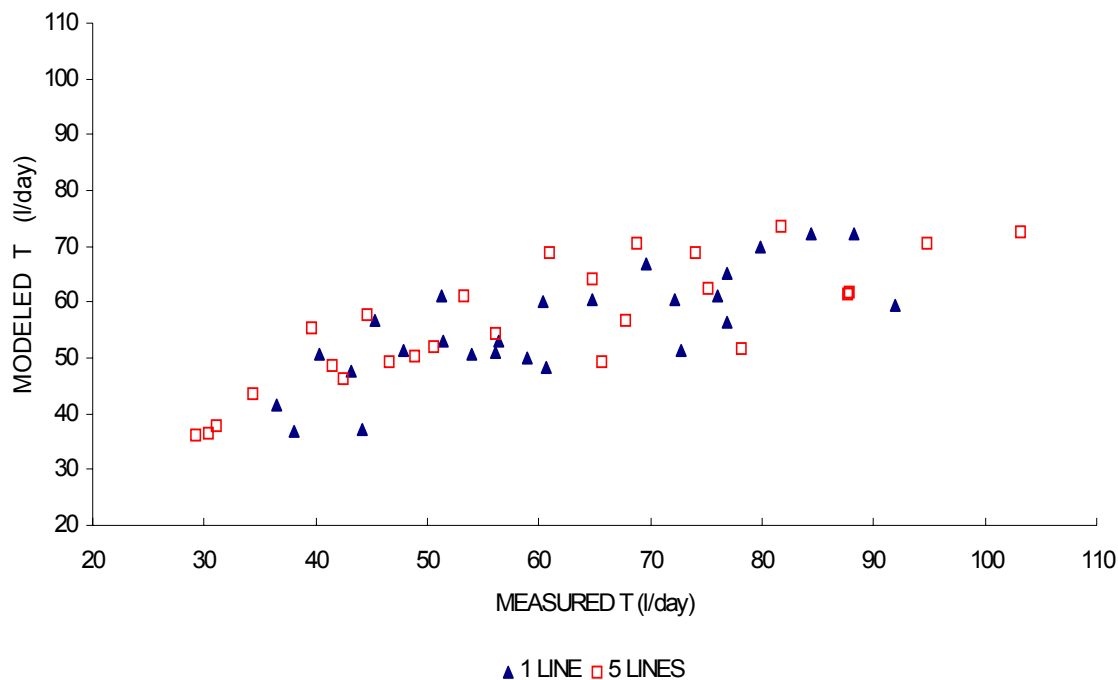


Figure 29 shows the daily variation of transpiration for both irrigation treatments, as estimated by the numerical model, on two days with different T_p : (a) May 6, 1994 ($T_p = 8.74 \text{ mm day}^{-1}$) and (b) May 8, 1994 ($T_p = 12.14 \text{ mm day}^{-1}$).

On the day with lower Tp (Fig. 29a), modeled T was 58.3 and 56.9 l day⁻¹ per tree for the treatment irrigated by five- and one-line, respectively. These values were higher than the average daily T measured in the same day with the heat-pulse technique (47.1 and 46.8 l day⁻¹ per tree for the same treatments, respectively). On this day, there were smaller differences between the treatments in modeled and measured T , than on the day with higher Tp . The numerical model gave maximum differences in T between treatments at midday, corresponding with the trend of field measurements.

On the day with higher Tp (Fig. 29b), modeled T was 70.7 and 67.1 l day⁻¹ per tree for the treatment irrigated by five- and one-line, compared with 69.6 and 66.9 l day⁻¹ per tree measured on the same treatments, respectively. On this day, larger differences in modeled and measured T were observed between the treatments, with the five-lines treatment showing higher T than the treatment irrigated by one-line.

Figure 30 presents the daily variations of modeled transpiration (T^*), transpiration measured on four trees per treatment (T) and the average daily transpiration per treatment (T_{avg}), during a period of 9 days in April 1994. In both treatments, estimated T values were very close to the T_{avg} . A good agreement between daily variations of modeled and measured T was observed in both irrigation treatments, confirming the sensitivity of the numerical model to changes in the micro-meteorological conditions during the period. The model gave higher transpiration rates during the period for the treatment irrigated by one line, matching the field measurements. Higher T rates in this treatment were a consequence of larger soil water availability than in the treatment irrigated by five lines during the period, because of a delay in the irrigation of the latter treatment.

Figure 29

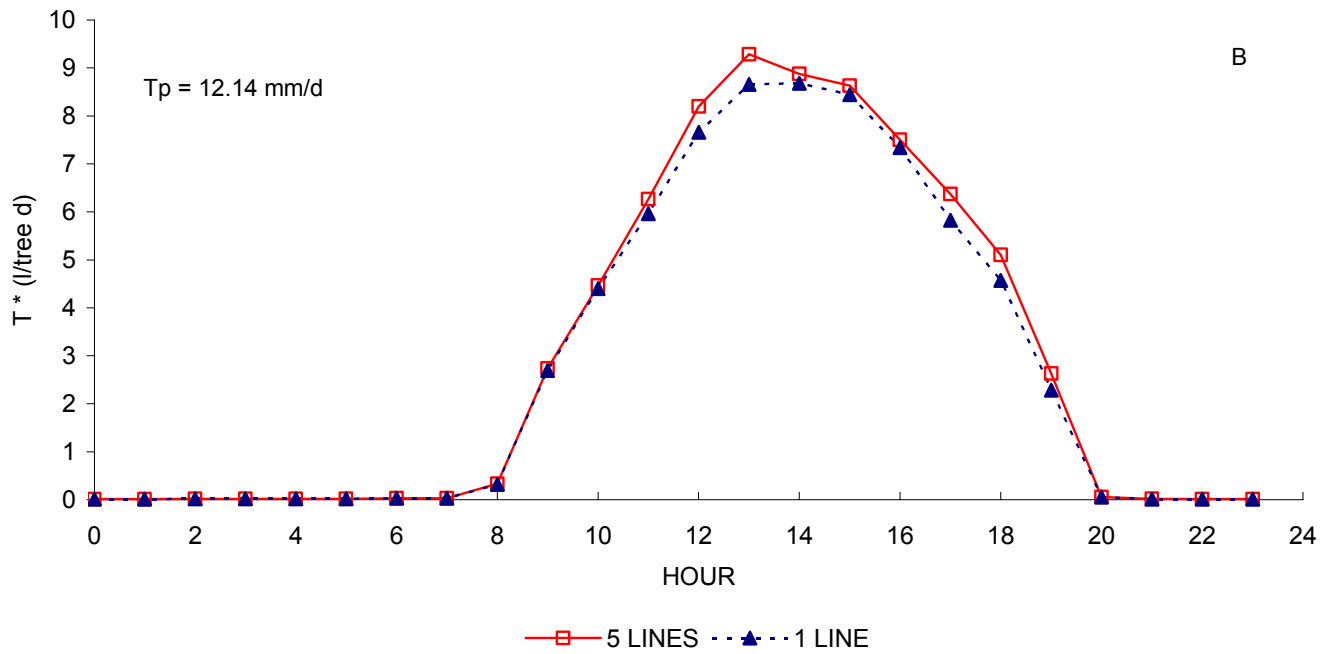
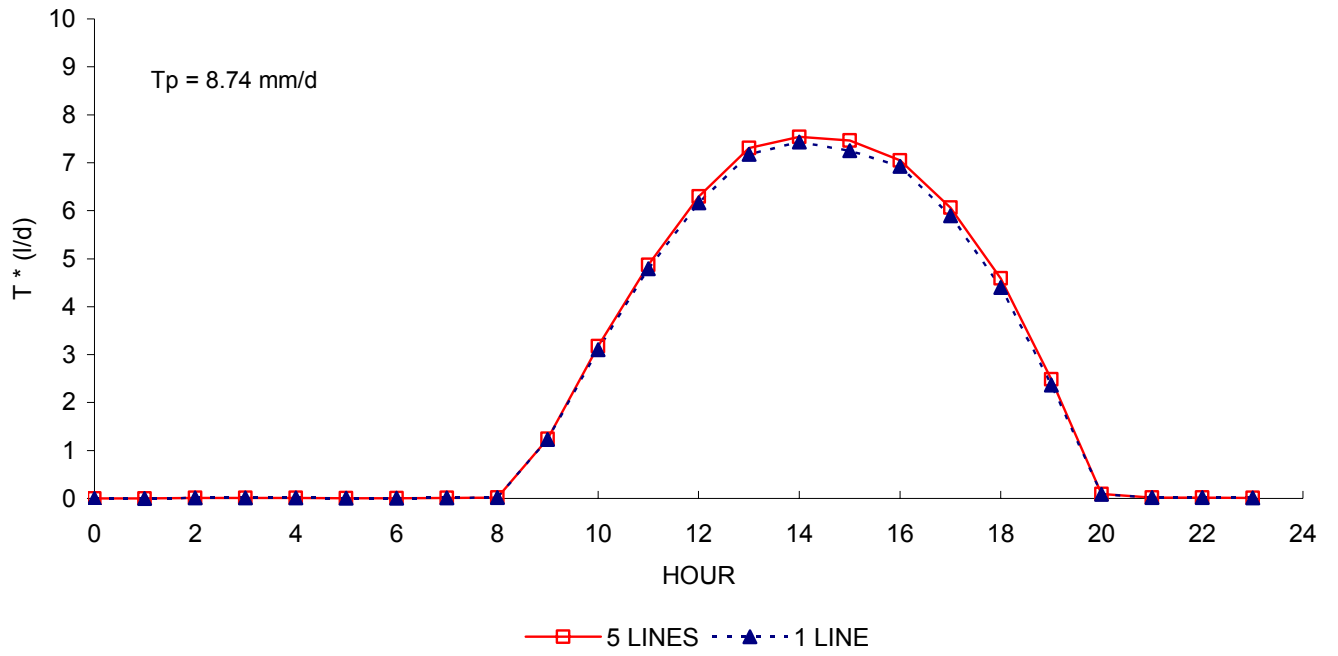


Figure 30

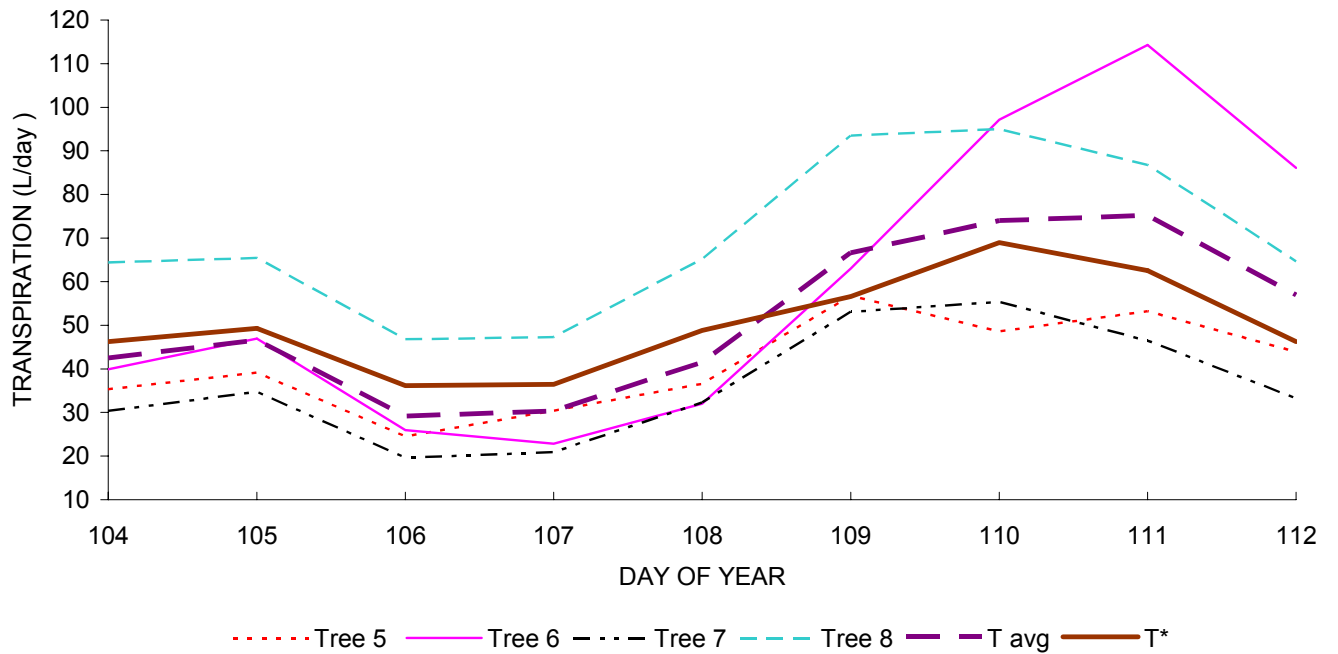
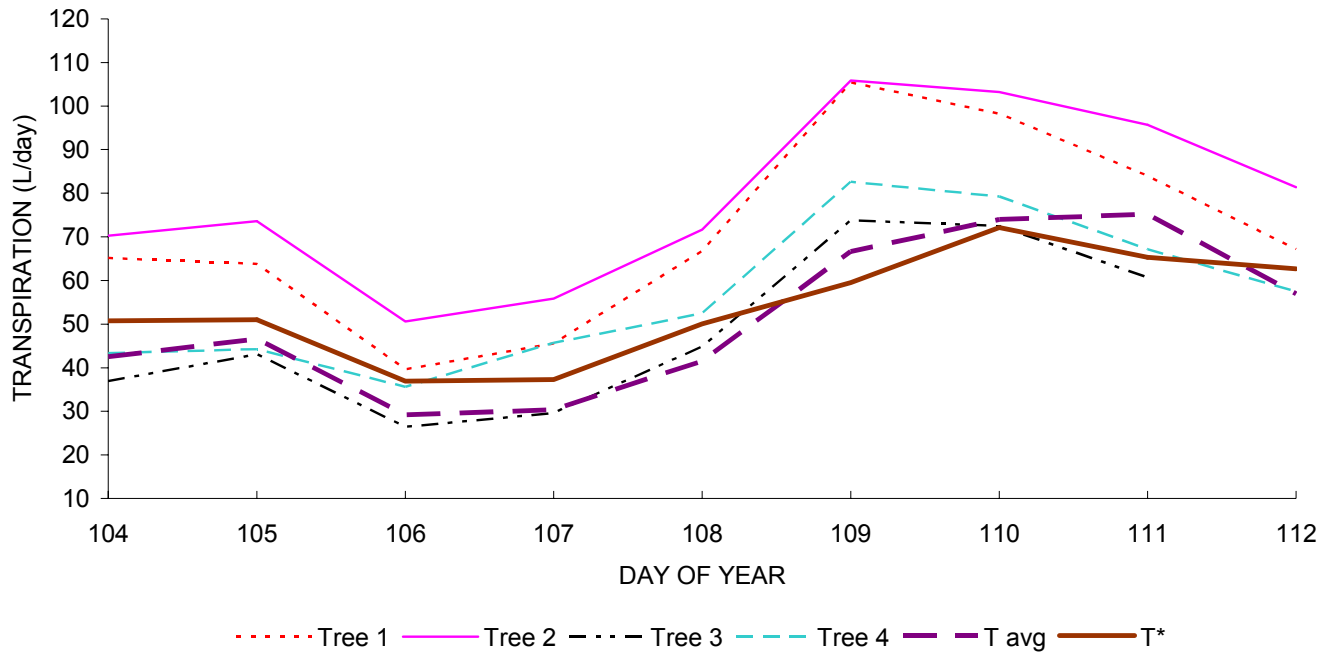


Figure 31 presents the diurnal cycles of net radiation (Rn), latent (H), sensible (E) and soil (S) heat fluxes over the orchard for both irrigation treatments, as estimated by the numerical model on a day with $Tp = 7.57$ mm day⁻¹. **Figure 32** shows the estimated energy fluxes for both treatments on a day with $Tp = 14.59$ mm day⁻¹. In both days, maximum values of Rn and E were registered between 12:00 and 14:00, while maximum S occurred between 11:00 and 13:00 h.

On the day with low Tp (Fig. 31), no appreciable differences were found between treatments in the diurnal course of the energy fluxes. Sensible flux in both treatments was close to zero during the daylight hours, and slightly increased at night.

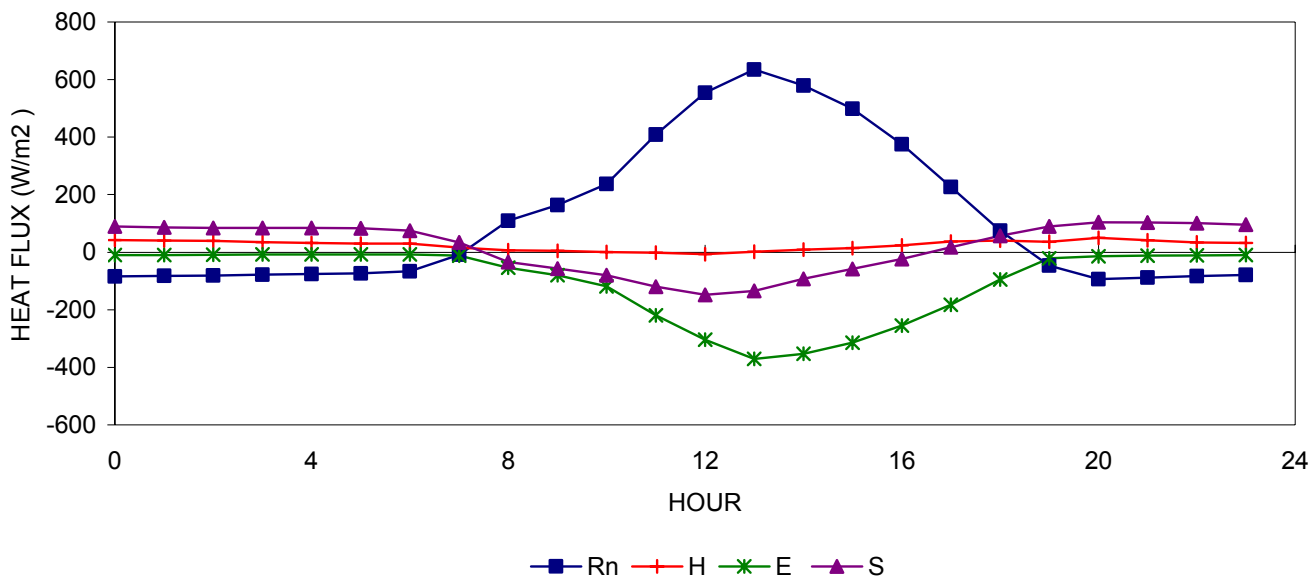
On the day with higher Tp (Fig. 32), Rn was lower than on the day with lower Tp , for both irrigation treatments. This was due to the restricted visibility, characteristic of extremely hot days at the experimental site. In both treatments, sensible and latent heat fluxes were considerably greater during the daylight period than on the day with lower Tp . Latent heat flux was as high as net radiation.

Figure 33 compares the diurnal course of canopy temperature estimated by the model (Tc^*) with continuous measurements made with fixed-position infrared thermometers (Tc_{stat}) and measurements collected three times per day with a hand-held infrared thermometer (Tc_{man}) on both irrigation treatments, on a day with low Tp (8.28 mm day⁻¹) and on a day with high Tp (10.32 mm day⁻¹) in April 1994. On both dates, good agreement was observed between the measured diurnal variations of canopy temperature and those predicted by the model. On the day with lower Tp the model predicted no differences between irrigation treatments in canopy temperature, while stationary measurements indicated a larger Tc for the treatment irrigated by one line. Manual measurements of canopy temperature were larger than stationary measurements, and did not indicate differences between the treatments.

On the day with higher Tp , the modeled midday Tc was larger in the single line treatment than in the treatment irrigated by five lines. Modeled Tc values in both treatments were slightly lower than stationary measurements, but they were very close to manual measurements made during the morning.

Figure 31

1 LINE - DOY 114



5 LINES - DOY 114

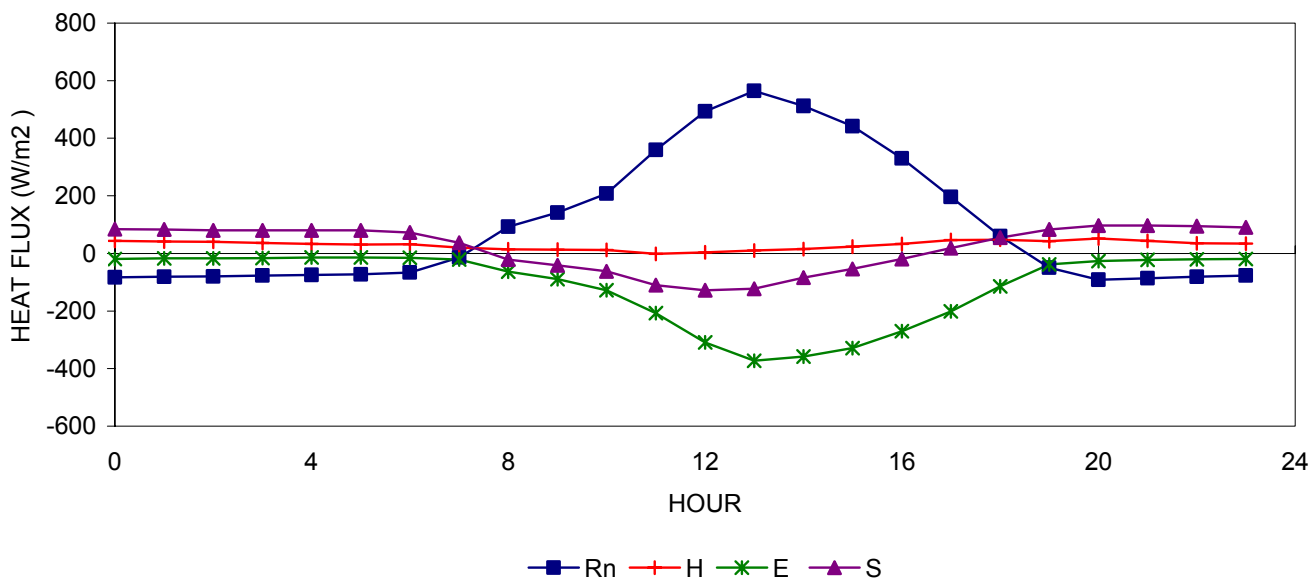
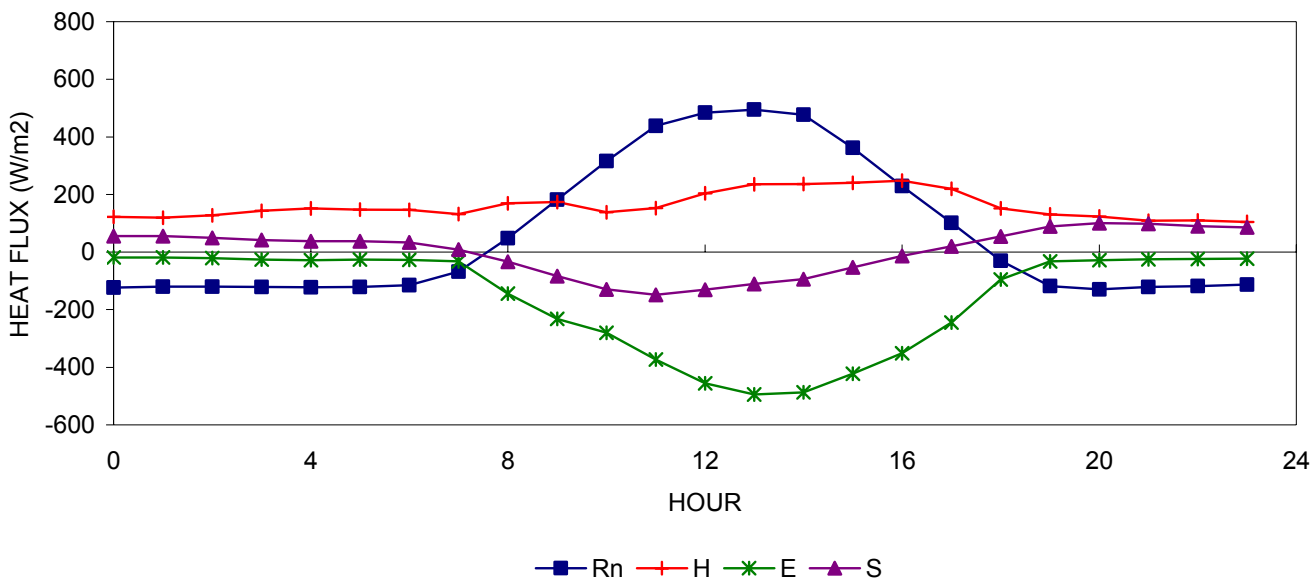


Figure 32

1 LINE - DOY 110



5 LINES - DOY 110

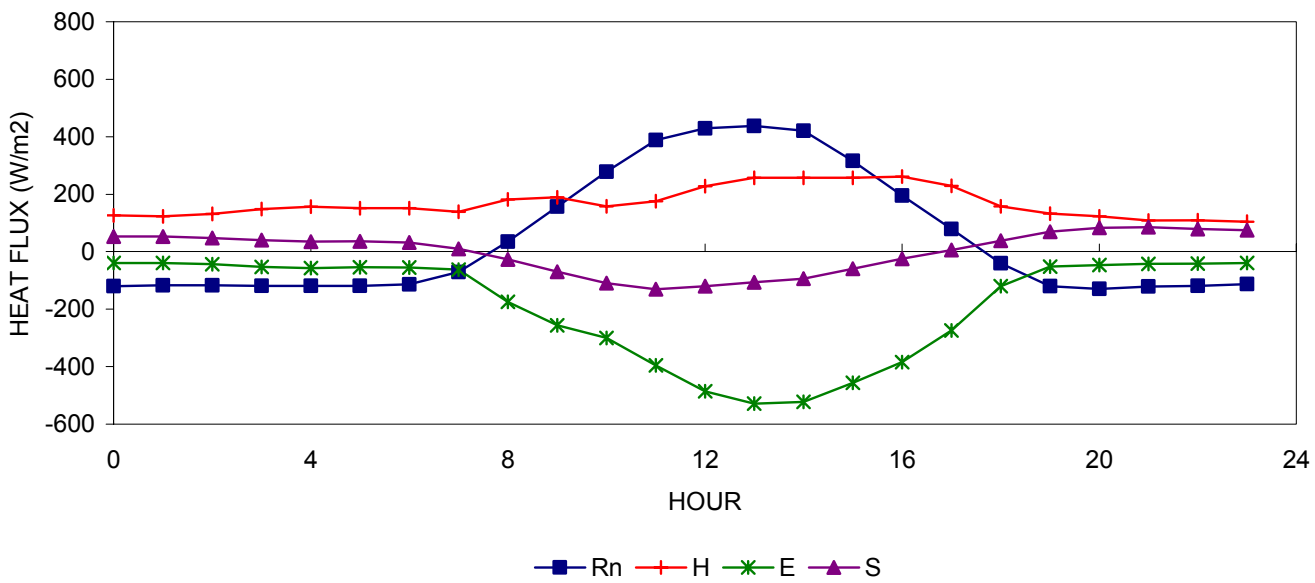
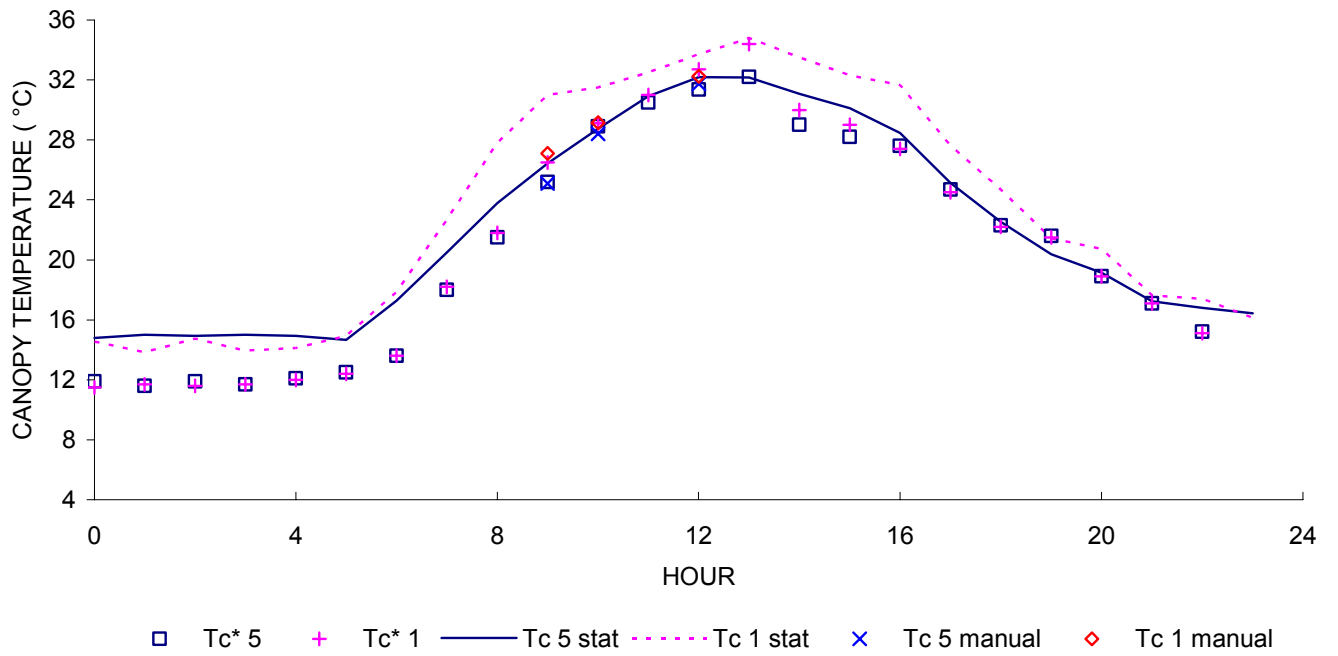
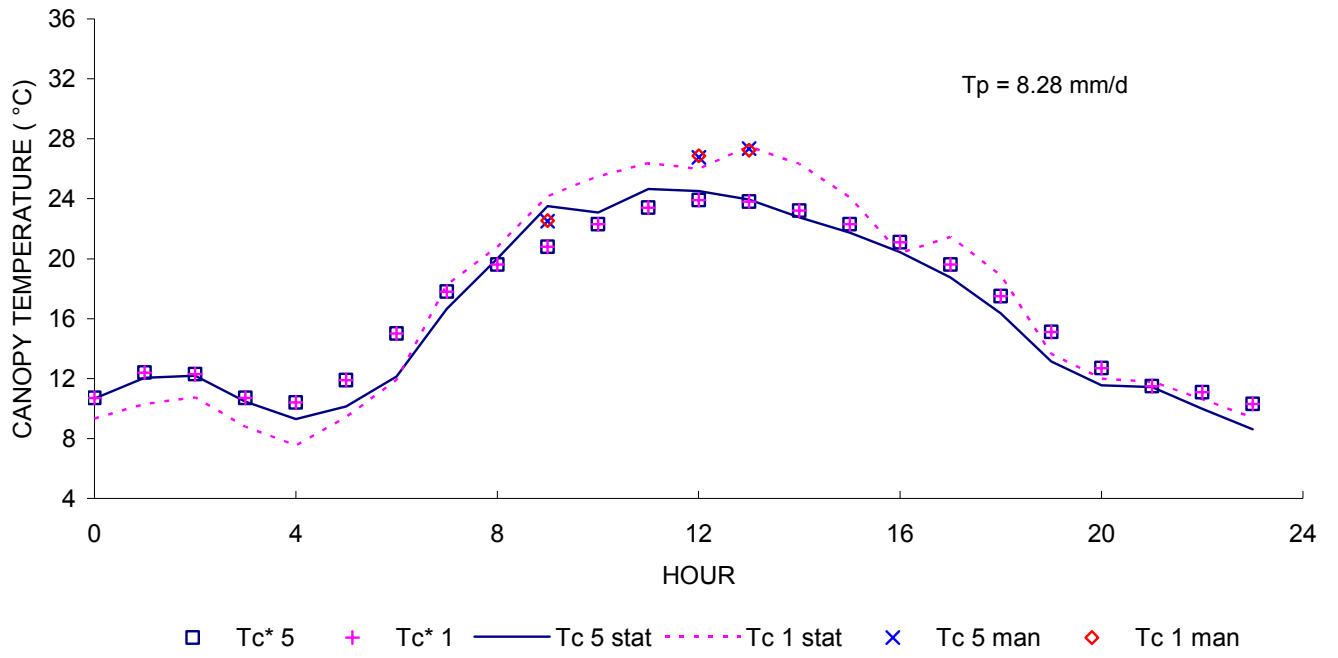


Figure 33



4.11 Effect of the irrigation treatments on yield

Analysis of yield data collected on eight trees per treatment during 1990-1994 did not show clear differences between the treatments (**Table 4**). Data in the table show the large variability of yield among years, characteristic of avocado trees. In the 1993 and 1994 seasons, the average yield of trees irrigated by one-drip line was higher than in trees irrigated by five-drip lines, but the extremely large standard deviation associated to the mean yield in both treatments, made any interpretation of these data meaningless for determining the effect of the irrigation treatments on yield.

TABLE 4. Mean annual yield and standard deviation (S.D.) recorded during the 1990-1994 in both irrigation treatments.

Year	Irrigation by 1-drip line		Irrigation by 5-drip lines	
	Mean yield (tonne du ⁻¹)	S.D.	Mean yield (tonne du ⁻¹)	S.D.
1990	1941	981	1988	775
1991	2254	737	2025	822
1992	138	178	235	217
1993	1004	167	873	435
1994	1629	574	1276	707

V. DISCUSSION

5.1. Application of the heat-pulse technique to measure sap flow velocity in avocado

The heat-pulse technique was found to provide accurate measurements of sap flow in avocado. Consistently with the results obtained in other species, sap-flow measurements in avocado underestimated actual transpiration value by 56%, very close to the factor found for citrus (50%), pine (53%) and eucalyptus (55%) with the same technique (Cohen, 1991). This agreement among species supports the accuracy of the technique for sap flow estimation.

In the calculation of avocado tree transpiration from sap-flow measurements, some difficulties were found in relation to the distribution of sap flow in the trunk cross-section. The presence of an active xylem tissue with appreciable sap flow at a depth of 48 mm below the bark, represented the main limitation to accuracy of transpiration estimates in avocado. Sap flow occurring at greater depths inside the trunk cannot be measured due to reduced accuracy of drilling, that makes the measurements at these depths unreliable. For this reason, sap flow in deeper layers of the trunk was computed by extrapolation of the sap flow in less deep layers, and this might introduce some error in the estimation of transpiration rate. This particular feature was observed in about 25% of the trees measured with the heat-pulse technique and it must be considered in future applications of this technique to the measurement of sap flow in avocado trees.

Another difficulty in the application of the heat-pulse technique in mature avocado trees was the effect of irregular trunk shapes observed in the orchard. Avocado trees have a very asymmetrical trunk shape, with very inclined trunks or, more frequently, the trunk bifurcates into two or more main branches close to the soil surface. These irregularities complicate the selection of experimental trees and the installation of heat-pulse sensors for sap-flow measurement in the field. In the case of trees with multiple branches a larger number of sensors is required.

With these limitations in mind, reasonably accurate estimates of avocado transpiration may, nevertheless, be achieved by means of the heat-pulse technique.

5.2. Avocado root growth response to wetted soil volume and temperature

The application of irrigation by five-drip lines caused the enlargement of the wetted soil area, as demonstrated by the results of measurements of soil water content distribution. This effect was translated into a more extensive distribution of active roots over a larger soil volume, thus reducing the competition for water which occurs under high root density. The other effect of the five-drip lines was the increased number of root tips and the

higher growth rates observed in the second irrigation season. We assume that one of these effects, or both together, contributed to an improvement in water uptake by the root system, achieved by the treatment when soil water availability was not a limiting factor.

The results of the present study confirm earlier reports on the close dependence of avocado root growth rate on soil temperature (Lahav and Trochoulis, 1981; Lomas and Zamet, 1994; Yousof et al., 1969). Nevertheless, the seasonal curves of root tip appearance and soil temperature in the root zone obtained in the present study did not coincide. Initial root growth in early spring seemed to be promoted by and coincident with the elevation of soil temperature, but subsequent variations in root growth during the season were not related to variations of soil temperature in the active root zone. These results may suggest that the main effect of soil temperature is to accelerate or delay the root growth response to internal tree factors which determine root growth.

It is interesting to note that the internal cycle of avocado root growth was not precisely regulated to achieve a favorable tree water status at critical physiological stages. For instance, the maximum root growth rate was recorded only after the flowering and early fruit in the spring. These physiological stages of avocado trees are known to be very sensitive to tissue water stress and require a maximum favorable tree water status. It is likely that this poor synchronization between root growth, on the one hand, and flowering and fruit set processes, on the other hand, may be responsible for the frequently poor productivity of avocado trees in this region.

5.3. Effect of the irrigation treatments on tree transpiration

During the first year of the experiment the irrigation treatments modified root distribution, but this effect was not consistently expressed in differences between the irrigation treatments, in tree transpiration. In the second irrigation season, higher transpiration rates were expected in the treatment irrigated by five-drip lines, due to the more extensive root system developed by trees in this treatment. In general, under non-limiting soil water availability higher transpiration rates were found in the treatment irrigated by five-drip lines. The increase in tree transpiration was assumed to be a result of an enlarged water uptake by the modified root system. However, differences in transpiration among the treatments were not continuous along the season.

In both irrigation treatments, a wide variability in transpiration between trees was observed. Considering the small number of replications used per treatment and the large standard deviation associated to daily transpiration

values, the comparison between means is not adequate for determining absolute differences in transpiration between the treatments.

The effect of enlarged water uptake capacity of increasing the transpiration rate, was not continuously expressed in the course of the interval between irrigations in the treatment irrigated once weekly by five lines. A reduction in transpiration was observed, starting from 4 days after the irrigation. This reduction in transpiration was considered to be an effect of the low soil water content at the end of the irrigation interval, and restricted the expression of the treatment's effect on tree transpiration to the beginning of the irrigation interval, when soil water availability was not a limiting factor. In spite of this, other results indicated that the enlargement of the wetted soil volume increased the tree capacity to maintain high rates of water uptake. This was expressed by the increased number of root tips per soil volume and by the decrease in tissue water deficit observed in the trees irrigated by 5-drip lines under extreme climatic conditions. However, it is possible that the change in the rate of water uptake caused by this treatment was not large enough to be detected by transpiration measurements made with the heat-pulse technique, especially in small trees. Therefore, the results suggest that a prolonged and positive effect of the irrigation by five-drip lines on canopy water status might be achieved by shortening the irrigation interval to 3-4 days.

The transpiration rate during the summer varied between 60 and 160 kg water day⁻¹ per tree, depending on tree size, physiological stage and climatic conditions. Considering a ground area of 36 m² per tree in the experimental orchard, these transpiration rates are equivalent to about 1.6 to 4.6 mm day⁻¹, which corresponds to 16 to 45% of the average potential transpiration in the Gilat site. The average transpiration rate observed in the orchard in the summer was about 2.5 mm day⁻¹. This rate is lower than the 3.1 mm day⁻¹ found during the summer in a citrus orchard, when similar techniques were applied. Low transpiration rates of avocado have been attributed by other workers to the adaptation of this species to semi-arid environments. The presence of a dense trichome cover on the tepals of the inflorescence and on young avocado leaves increases the boundary layer resistance and reduces transpiration. Additionally, an abundant epicuticular wax layer covering the avocado stomata has also been associated with the low transpiration rate of avocado leaves (Blanke and Lovatt, 1993).

5.4. Effect of the irrigation treatments on the transpiration response to climatic conditions

The response of avocado tree transpiration to the applied irrigation treatments was influenced both by soil water availability and by climatic conditions. When soil water availability was not restricted, the enlargement of wetted soil volume by root growth modification improved the response of avocado transpiration to variations in evaporative demand. During periods of high evaporative demand, the trees irrigated by five dripper lines showed higher transpiration rates than the trees irrigated by a single line.

Under non-limiting soil water supply and developed leaf canopy, avocado trees can increase their transpiration at a higher rate than that of potential transpiration. This was expressed as a clear linear relationship found between T/T_p and T_p in both irrigation treatments under such conditions. However, no significant differences were observed between the treatments. This finding may be attributed to the reduced sensitivity of transpiration measurements to detect small differences in water uptake between the irrigation treatments.

The capability of avocado trees to increase transpiration at a higher relative rate than the increment in T_p is an interesting response which needs further consideration. In the present study the values of potential transpiration were calculated from the combined Penman-Monteith equation, as modified by Fuchs et al. (1987). We analyzed two simulations of this model, using parameters measured in the experimental avocado orchard, in order to test the variation of the T/T_p ratio under conditions of high evaporative demand. **Figure 34** shows the model simulation of the T/T_p ratio variation with increasing values of (a) air temperature and (b) air relative humidity, for different canopy stress levels. The levels of canopy stress were defined by introducing three canopy conductances: 0.10 cm s^{-1} for a non-stressed canopy (Sterne et al., 1977), 0.08 cm s^{-1} for moderate stress conditions and 0.05 cm s^{-1} for severe stress conditions. The figure shows that the T/T_p ratio increases with increasing air temperature, irrespective of the water stress level. On the contrary, a negligible effect of relative humidity on the T/T_p variation was found. The model simulation confirms that, from a theoretical point of view, the avocado T/T_p ratio may increase under conditions of high evaporative demand caused by high air temperatures, as our field measurements indicated. This situation can only occur if the stomata remain open and no limitations to available soil water are imposed. Avocado stomata tend to open as the air temperature increases above the normally encountered range, thus allowing increased canopy water loss. Avocado stomata respond to temperature variations faster than they do to changes in air humidity, recalling the subtropical origin of this species. The physical interpretation of the avocado transpiration response to high evaporative demand is based on the assumption that, as the air temperature increases and intensifies the atmospheric evaporative demand, leaf temperature will increase at a higher rate than air temperature, for a given stomatal resistance. Higher leaf temperature will then increase the saturated water vapor pressure in the

substomatal chambers of the leaf, hence promoting evaporation and water loss rate from the canopy, which explains the increase in the T/T_p ratio.

In the Gilat site, where the present experiment was carried out, the main factors affecting the variations of T_p within days are air temperature and relative humidity. **Figure 35** shows the daily course of (a) potential transpiration, (b) wind speed, (c) solar radiation, (d) relative air humidity, (e) air temperature and (f) vapor pressure deficit, measured on two days with different T_p (May 20, $T_p = 11.33 \text{ mm day}^{-1}$ and May 22, $T_p = 9.48 \text{ mm day}^{-1}$) in the meteorological station located outside the experimental orchard.

As shown in the figure, the difference in T_p between the two dates is mainly explained by differences in air temperature and to a less extent, by differences in air relative humidity registered in the site. Other meteorological variables, such as wind speed and solar radiation did not contribute significantly to the difference in T_p values between the two dates.

Figure 34

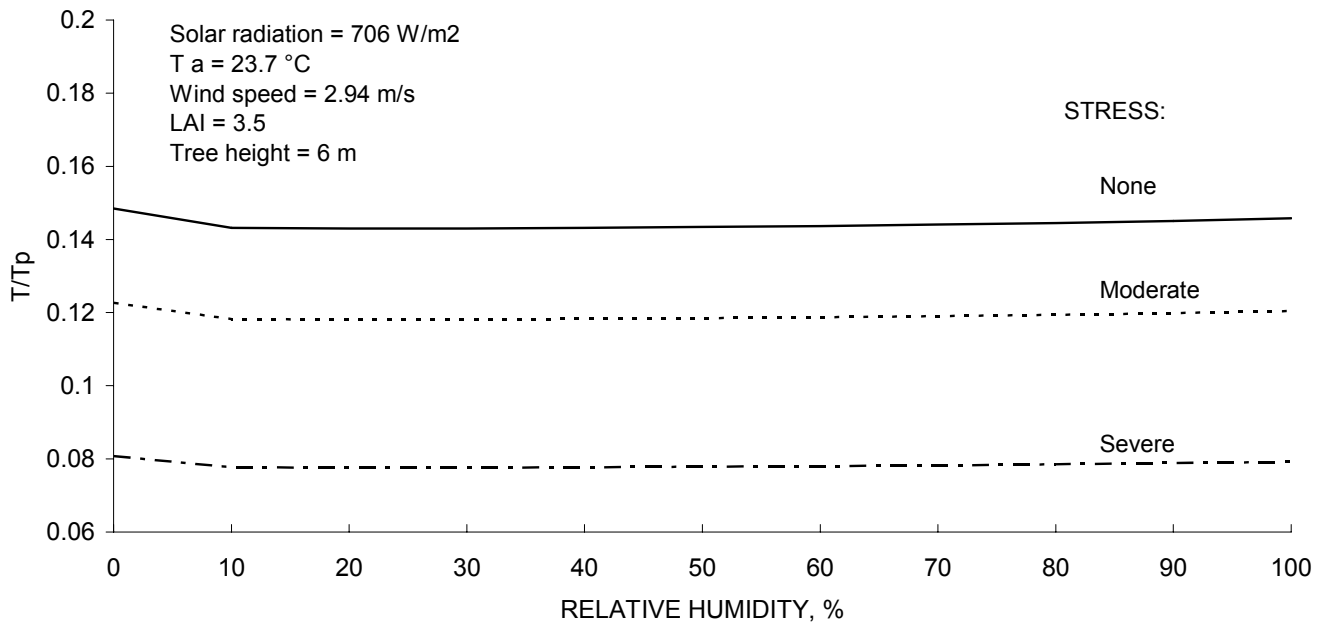
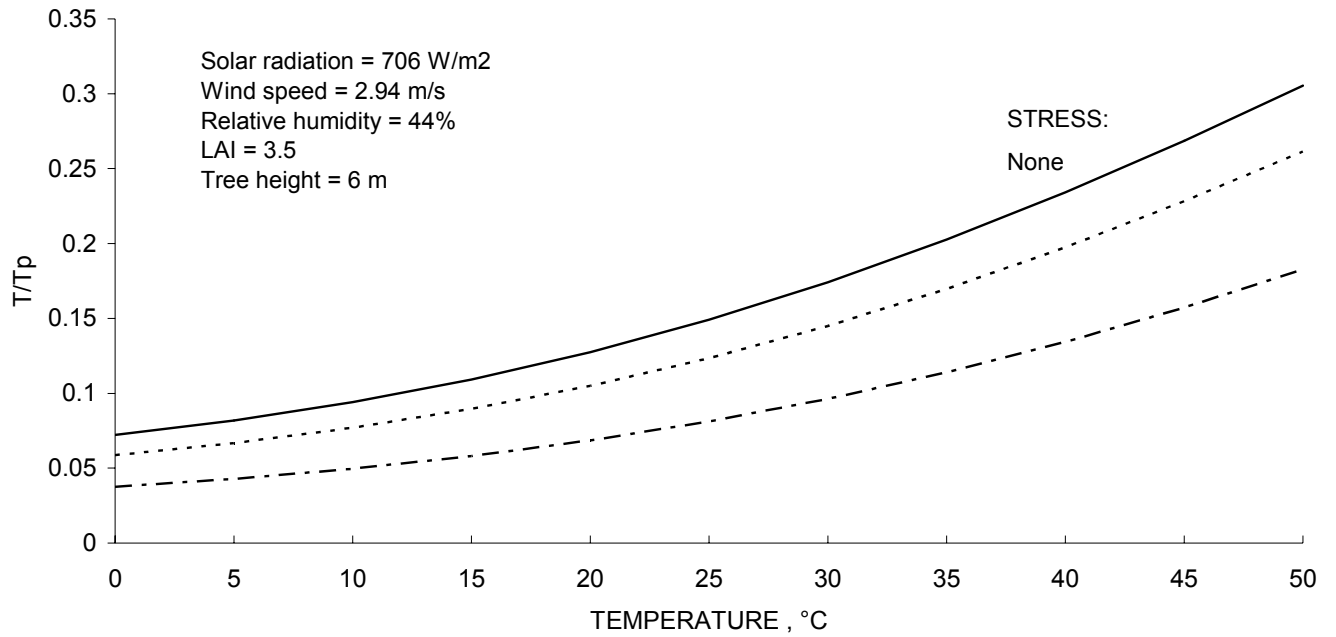
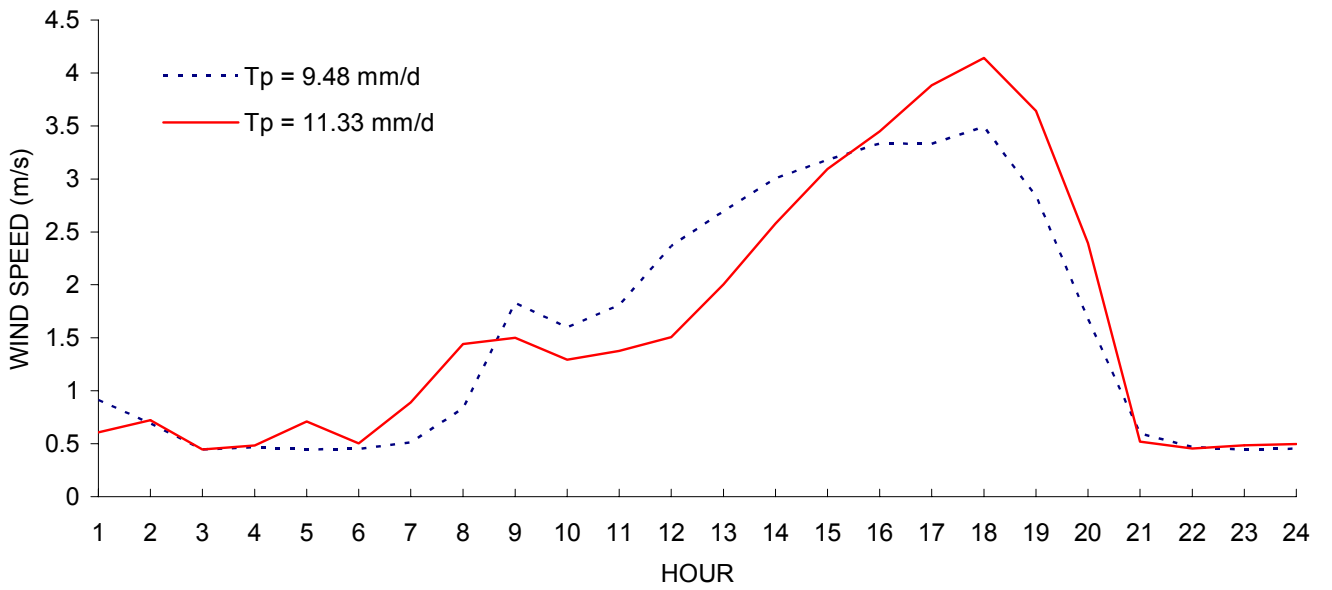
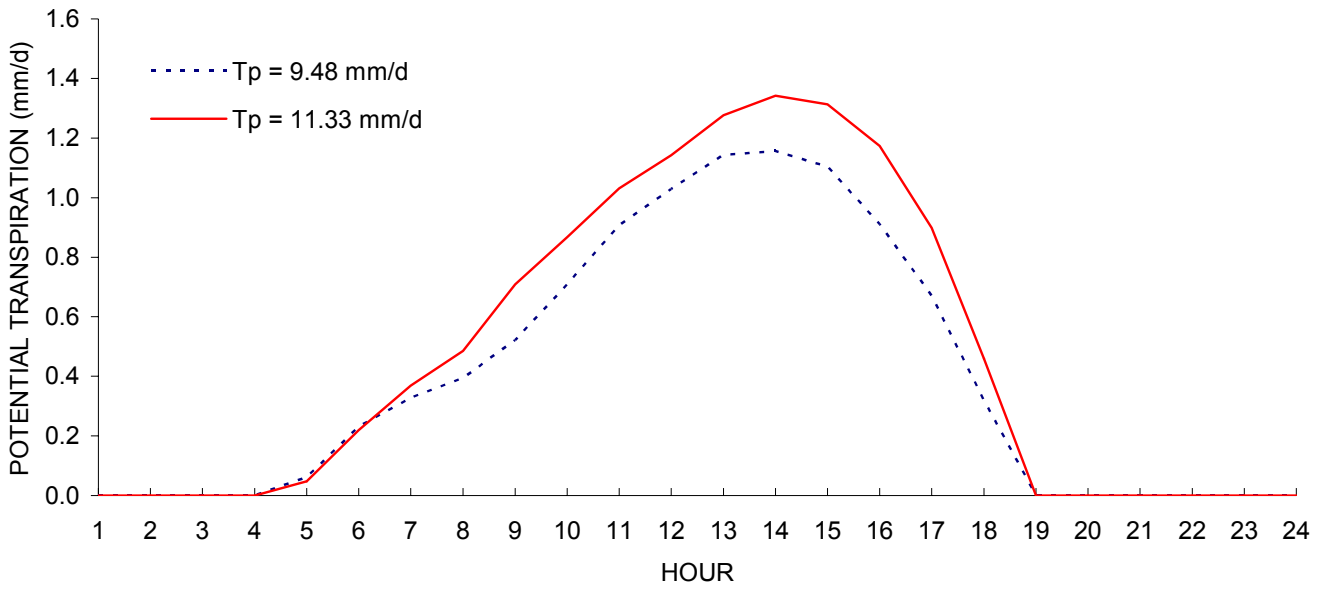
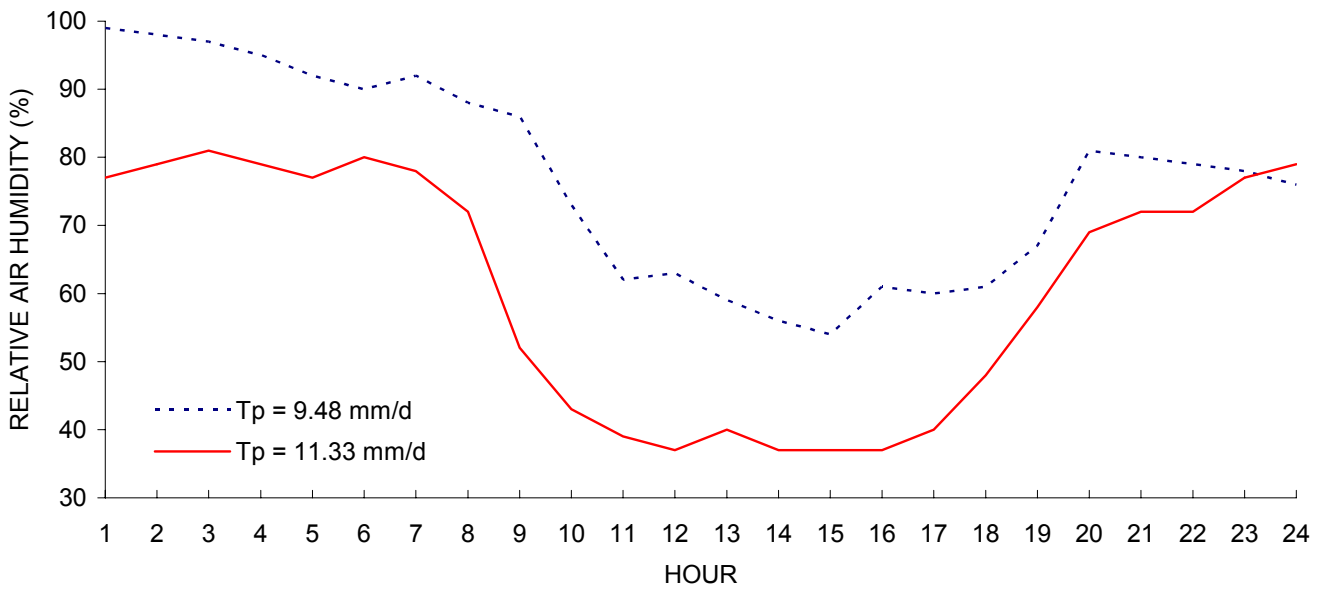
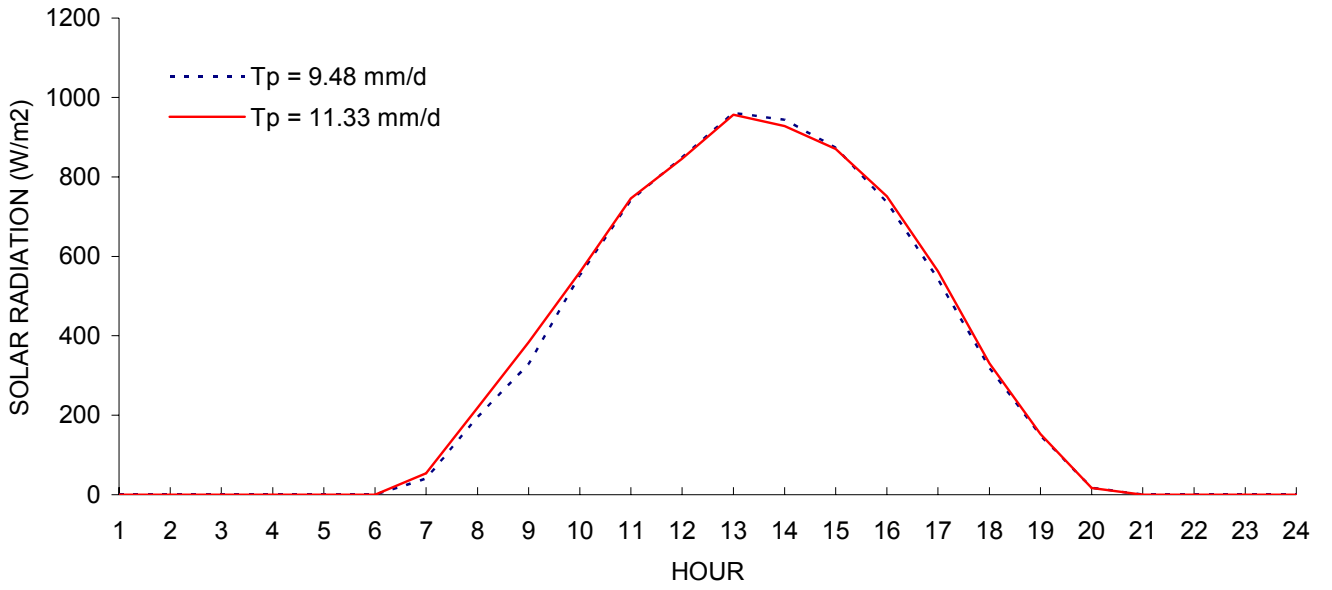
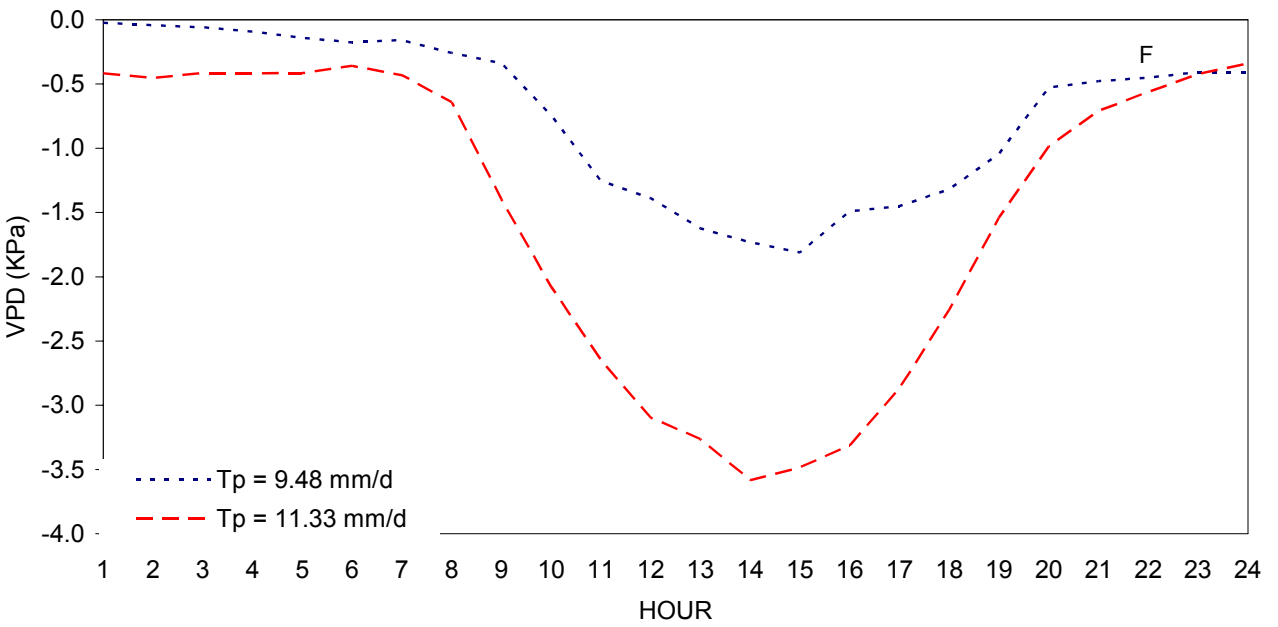
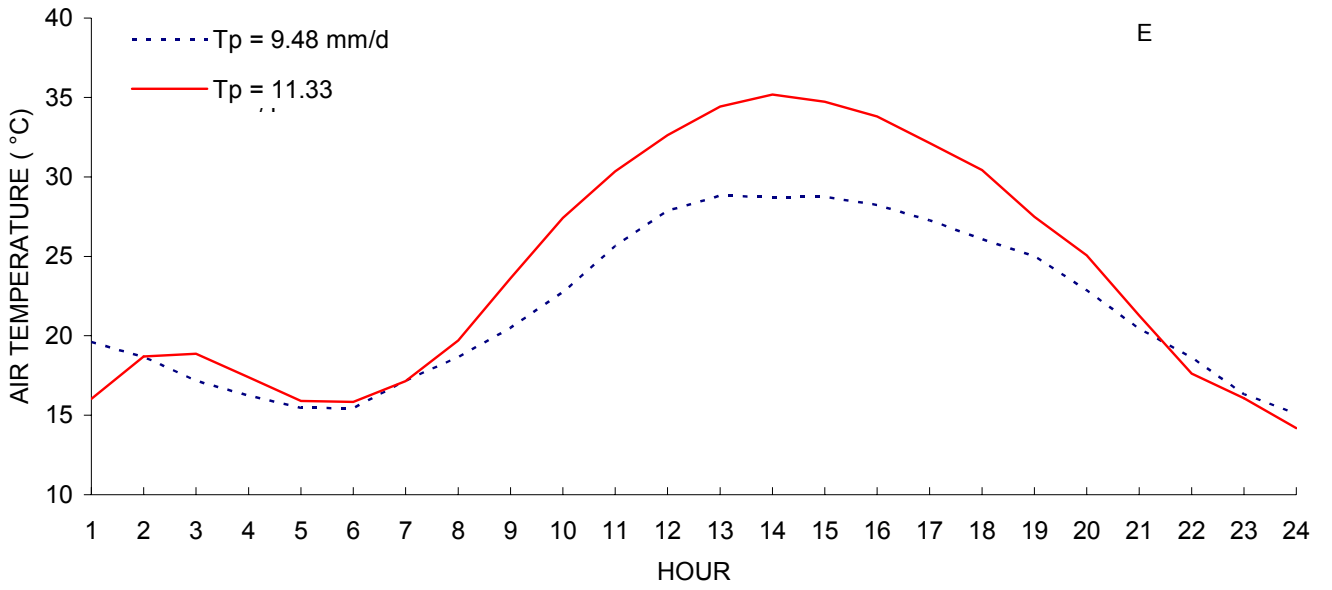


Figure 35







5.5. Avocado canopy water status response to increased wetted soil volume during periods of severe climatic conditions in the flowering and fruit-set season

Measurements of leaf water potential and canopy temperature made on days with non-limited soil water availability during the flowering and fruit-set stages, indicated the development of water stress in the canopy of the single-line irrigated trees under conditions of high atmospheric demand, confirming a better canopy water status in the trees irrigated by five lines.

Canopy conductance of the trees, represented by the T/T_p ratio, increased with higher T_p in both irrigation treatments. In the summer, this increase in T/T_p was observed even at high T_p rates ($>11 \text{ mm day}^{-1}$). In the early spring, T/T_p increases linearly with T_p up to 10 mm day^{-1} , and then remains constant, consistent with previous observations on citrus trees (Cohen et al., 1987).

One of the factors that may limit the T/T_p response of avocados to high atmospheric demand conditions in the early spring is the absence of leaf surface area, due to a severe leaf shedding observed in the orchard in the anthesis peak. Although avocado floral organs may significantly increase canopy water loss, the reduction in leaf surface area during the flowering period has a greater impact on tree transpiration, thus explaining the limited response of transpiration rate to conditions of high evaporative demand, observed in both irrigation treatments during this stage. The lack of continuous measurements of leaf area throughout the season made it impossible to quantify the impact of seasonal variations of canopy structure on tree transpiration. However, further evidence is found in the literature, of the detrimental effect of leaf shedding on the productivity of flowering avocado trees. Zilkah et al. (1989) related the reduction in leaf area, observed during the flowering period of avocados in Israel, to an intensified fruit drop and lower yield. They suggested that the presence of leaves during the flowering period is essential to support the growth of young fruits, and also to reduce fruit drop caused by heat stress. Leaves are a sink for water transport through the tree. They provide evaporative cooling by transpiration and supply the young fruits with shade to protect them from direct radiation.

The results obtained in this study suggest that irrigation scheduling of avocado trees in the flowering season must be optimized in order to supply the trees with the correct amount of water to satisfy their requirements, considering the low water use of the flowering trees, caused by their reduced canopy leaf surface.

5.6. Application of a soil-plant-atmosphere numerical model to estimate orchard transpiration and canopy temperature

Transpiration estimates obtained from a one-dimensional numerical model developed by Avissar et al. (1986) underestimated average values measured in the field by 11%. When transpiration was expressed in units of l day^{-1} , a good correlation was found between estimated and measured values ($R^2=0.59-0.60$). These results confirm the ability of the numerical model to estimate actual transpiration. However, it must be also taken into account that the model considers the vegetation as a bulk layer for computing energy fluxes, so that final estimates are not expected to be as accurate as those obtained with models that consider a more sophisticated description of the canopy structure.

The model was able to predict differences in transpiration between treatments. On days with high T_p and under unrestricted soil water availability, the transpiration rate estimated for the five-line treatment was larger than that estimated for the treatment irrigated by a single line, which matched the trend of the field measurements. Variations in estimated and measured T during the flowering and fruit-set stages indicated a good agreement between modeled and measured values in both irrigation treatments, confirming the sensitivity of the numerical model to changes in the micro-meteorological conditions during the period.

The numerical model allows a more detailed examination of the observed differences in net radiation, soil, sensible and latent heat fluxes, between days with different levels of atmospheric evaporative demand. Analysis of net radiation (R_n), latent (H), sensible (E) and soil (S) heat fluxes estimated by the model on days with high evaporative demand indicated important increases in sensible and latent heat fluxes in both irrigation treatments, compared with days with lower evaporative demand. Under conditions of high evaporative demand registered in the experimental site, the latent heat flux increased and equaled the R_n flux. This may be due to the horizontal advective transport of heat from surrounding areas into the orchard, which increases evaporation from the leaves and results in lower temperatures near the crop than in the air above the crop - known as the "oasis effect".

Canopy temperature estimates obtained with the model were in good agreement with measurements collected in the field with both hand-held and fixed-position infrared thermometers. Predicted values were 2-3°C lower than measurements obtained with fixed-position infrared-thermometers. When compared with manual measurements, predicted canopy temperature values were more accurate. The model did not always indicate differences between the irrigation treatments in the diurnal course of estimated canopy temperature.

VI. CONCLUSIONS.

Increasing wetted soil volume resulted in a more extensive distribution of avocado roots in the upper soil layers. Enlargement of the root system by increasing the wetted soil volume allows a higher transpiration level and improves the transpiration response of the trees to variations in the atmospheric demand under non-limiting soil water availability, as a result of a larger soil water uptake by the roots.

Under unrestricted soil water availability and with a fully developed leaf canopy, transpiration of avocado trees increases relatively faster than the potential transpiration. This characteristic of the tree allows the maintenance of a favorable canopy water status for normal physiological activity, even under conditions of high atmospheric evaporative demand. However, this response may vary under conditions of soil water deficit or when the canopy evaporative surface is limited. This particular response of avocado transpiration to climate should be analyzed in detail, and more experimental work is required in order to achieve a better comprehension of the factors determining this response.

The water status of flowering avocado trees under conditions of high atmospheric demand can be improved by promoting higher root growth rate and maintaining a continuously high water availability in the soil. An increased wetted soil volume was found to be a practical mean of promoting root growth and improving the tree water uptake. Results of measurements of the tree transpiration and the diurnal variations of canopy temperature and leaf water potential indicated a significant improvement of water status in flowering avocado trees that were grown on a large wetted soil volume with an expanded root system distribution.

During the flowering period of avocados, the increased transpiration in response to higher potential transpiration levels is restricted to T_p of 10 mm day⁻¹. At higher T_p values, avocado transpiration does not show any further increase and does not respond to variations in T_p , even if soil water availability is optimal. These findings indicate the effect of a tree-specific factor in limiting the avocado transpiration response to conditions of high atmospheric demands during the flowering period. Severe leaf shedding occurring in the anthesis peak considerably reduced the leaf surface area of the trees. This reduction in canopy leaf area might explain the low water use of flowering avocado trees and the restricted transpiration response to variations in the atmospheric demand during this period.

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