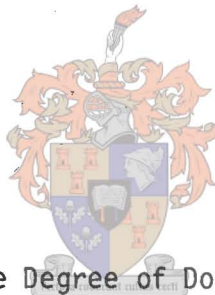# Interrelationships, among Soil Water Regime, Irrigation and Water Stress in the Grapevine (<u>Vitis</u> <u>vinifera</u> L.)

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Dissertation presented for the Degree of Doctor of Philosophy in Agriculture at the University of Stellenbosch

Promoter : Prof. J.H. Visser

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En in die bitterheid van die droë somerskaarste, as jou bone
se bloeisels afval en jou mielietjies krimp inmekaar en jou
bome druip verdrietig sodat nog één week tot by die volgende
beurt hulle onherstelbaar sal vernietig: as jy nie almal
kan natkry nie en jy weet nie watter om maar oor te laat
nie; en die ou watertjie sypel, so stadig, so stadig, en
die ure van jou beurt vlieg verby - my leser, dan bestu-
deer jy holtetjies en sandplekkies baie fyn om maar nie 'n
druppeltjie op die pad te verkwis met onnodige weglek en
opdam nie. Daarom is besproeiing so 'n hartstog by my.

<div align="right">- C.J. LANGENHOVEN</div>

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search work was undertaken.

- My wife, Regina and my two sons Abrie and Ernst for their patience and
support. They had to do without me on many occasions.

- My Heavenly Father to whom I belong.

CONTENTS

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LIST OF ABBREVIATIONS

CT   -   Canopy temperature

FC   -   Field water capacity

LWP   -   Leaf water potential

LWP_{14} -   Leaf water potential at 14h00

LWP_p -   Pre-dawn leaf water potential

PA   -   Photosynthetic activity

PAM   -   Plant available moisture

PAR   -   Photosynthetic active radiation

PWP   -   Permanent wilting point

RH   -   Relative humidity

Rs   -   Stomatal resistance

SWC   -   Soil water content

SWP   -   Soil water potential

Tl   -   Leaf temperature

TSS   -   Total soluble solids

TTA   -   Total titratable acidity

CHAPTER 1

INTRODUCTION

Agriculture consumes about 70% of South Africa's limited available water, making it imperative to obtain optimum returns with regard to yield, quality and profitability per unit volume of water. Approximately 113 000 ha of land are planted to grapevines for the purpose of wine making, drying, table grapes and progagation. Wine grapes, the subject of this investigation, account for more than 90% of the area under vines. The majority of these wine grape vineyards are irrigated and even in traditionally dryland districts new water schemes offer the possibility to further increase the area of irrigated vineyards. Irrigation programmes vary from only one irrigation annually in some vineyards, to daily trickle irrigation, totalling more than 1 000 mm in the hot regions.

The rapid development, and adoption in practice, of new permanent irrigation systems, especially tricklers and micro-jets, put high irrigation frequencies and high soil water potentials with resultant luxurious growth conditions at the disposal of the farmer. Detailed scientific information of vine response to these irrigation practices is scarce, not only in South Africa, but world-wide. Consequently, managerial difficulties, wastage of water, poor wine quality, unbalanced grape/shoot mass ratios and sub-optimal irrigation system design are often encountered in South African viticulture.

Not only does the scarcity of water and the need to conserve this commodity provide a strong stimulus for irrigation research, but it is a known fact that irrigation affects must composition and wine quality. The latter

effect is not surprising since water affects most known processes in the plant. Furthermore, both extremes of water supply viz., over-supply and drought conditions, are deleterious to wine quality. The pertinent question revolves therefore around the optimum soil water regime between the two poles of water supply. However, the 'best' water regime depends on the objective of the researcher or farmer. Maximum yield probably requires a different irrigation approach than maximum quality and the requirements for root growth do not necessarily comply with the water needs of the shoots. Strong pressure is also exerted by the International Wine Office (OIV) on member countries, including South Africa, to satisfy only the minimum water requirements of wine grapes and to focus viticulture more on quality than on quantity. The present over-production of low and medium quality wines confirms the wisdom of this approach.

Vine response to irrigation is also dependent on soil, climate, cultivar and viticultural practices. Successful irrigation research thus depends on a broad approach which takes account of all these factors. This investigation was partly conducted in a glasshouse as well as in open air pots under more controlled conditions than those encountered in the field, in order to assess grapevine response to soil water regimes. However, the principal investigation was carried out in a specially established experimental vineyard of 3,8 ha near Robertson in the Breede River valley. The experimental site represented a typical soil in an important irrigated viticultural area and a cultivar highly recommemded for the region was used. The research was aimed at ultimately relating grape yield, growth and quality parameters to irrigation scheduling and to a few irrigation systems. It was attempted to relate vine performance to the more fundamental plant processes such as growth of the different organs and response of certain plant parameters. This approach led to a better understanding of the nature of vine water

stress and makes extrapolation of results to other climatic regions possi-
ble.

CHAPTER 2

A PRELIMINARY INVESTIGATION INTO FACTORS RELATING TO THE ONSET OF WATER STRESS IN GRAPEVINES : A GLASSHOUSE STUDY

INTRODUCTION

Successful irrigation scheduling depends largely on the timing of water applications. This important decision is in practice based on a 50% extraction of total available water in the soil i.e. 50% of the quantity between field water capacity (FC) and a soil water potential of -1 500 kPa (permanent wilting point), thus solely based on soil factors. However, water in the plant is rarely in equilibrium with soil water (Begg & Turner, 1976). There are in fact, three important factors involved in the development of water stress viz., transpiration rate, rate of water movement from soil to roots, and the relationship of soil water potential to leaf water potential (Kramer, 1983). It is consequently widely recognised that the most reliable indicators of plant water status are measurements made on the plant itself. In recognition of this fact, the concept of profile available water capacity (PAWC) which relies on a plant parameter to indicate the lower limit of available water, was adopted (Hensley & De Jager, 1978; Hensley, 1980).

In order to define a lower limit of available water, it is important to detect the onset of water stress or water deficits in plants as early as possible, before water potential and turgor decrease low enough to interfere with normal functioning (Kramer, 1969). Literature abounds with evidence to show that deficits affect every aspect of plant growth, including anatomy, morphology, physiology and biochemistry if the water stress is severe enough and lasts long enough (Hsiao et al., 1976). According to Oosterhuis (1982), however, a prerequisite for a useful indicator of

crop water stress is sensitivity, reliability and easy recognition or detection.

The latter aspect is of particular importance if irrigation is to be scheduled according to plant indicators. If plant indicators of water stress are only used to calibrate soil or climatological parameters, plant parameters which are not easily recognised, also offer possibilities. This literature study deals only with indicators of water stress relevant to the present study and a few others which, according to literature, are very promising.

General Aspects of Water Stress

Water deficits develop when transpirational water loss exceeds root absorption. This happens to most plants on hot sunny days even when soil moisture is not limiting. Such transient water deficits can be attributed to the resistance to water flow from the soil into the root xylem. Consequently water will flow from vacuoles of turgid parenchyma cells to evaporating surfaces whereupon the water potential of cells from which water is lost, drops. Water in the plant is obviously limited and on hot days the water content of the plant as a whole becomes so low that most of the water lost in transpiration, comes directly from the roots (Kramer, 1983).

Prolonged stress caused by decreasing availability of soil water is of more importance to vineyards. Long term water deficits in plants commence as described above, but gradually as soil water potential decreases, plants are unable to recover at night (Slatyer, 1967). The water potential of the soil thus sets the possible limit of recovery by the plant at night so that the daily maximum water potential of leaves and roots follow the decline in soil water potential down to, and beyond wilting point (Begg & Turner, 1976). Permanent wilting point is determined by the osmotic characteristics of the

plant and is not a characteristic of the soil. It usually occurs at a soil water potential of about -1500 kPa because plants usually wilt at that water potential (Slatyer, 1967).

The effect of water deficits on crop growth and development is further complicated by the fact that plants, including vines, differ in sensitivity towards water stress during different stages of development (Kasimatis, 1967; Begg & Turner, 1976; Van Zyl, 1981). Each organ and physiological process may also respond differently to increasing water stress. Hsiao (1973) listed a number of plant parameters in sequence of decreasing sensitivity towards water stress. Differences among plant organs as regards their response to water deficits can at least partly be attributed to their ability to compete for water. This competition is a function of factors such as exposure, stage of growth, differences in osmotic potential and internal resistances to water flow, which eventually lead to water potential gradients and redistribution of water in the plant (Kramer, 1983). In grapevines, younger leaves compete for water at the expense of older leaves, (Kasimatis, 1967) most probably through the mechanism of better exposure, more rapid transpiration and the subsequent water potential gradient (Kramer, 1983).

Plant Morphological Indicators of Water Stress

It is generally accepted that the reduction in cell growth is one of the most sensitive indicators of plant water stress and that other processes are affected in sequence as more severe water deficits develop (Hsiao, 1973; Begg & Turner, 1976; Hsiao et al. 1976; Begg, 1980; Kramer, 1983). Conflicting reports exist as to which of cell enlargement or cell division is affected most by water stress (Kramer, 1983), but Hsiao (1973) came to the general conclusion that cell enlargement is more inhibited than cell

division. Some of the most important consequences of this sensitivity of cell growth to small water deficits is a marked reduction in leaf area (Begg, 1980; Oosterhuis, 1982; Kramer, 1983) also experienced in grapevines (Eibach & Alleweldt, 1983), a decrease in the shoot elongation rate of grapevines (Vaadia & Kasimatis, 1961; Eibach & Alleweldt, 1983; Van Zyl & Kennedy, 1983) and in the elongation rates of newly formed internodes and tendrils (Smart & Coombe, 1983). Once leaf area development is completed, leaf movements provide an effective strategy for reducing radiation interception and the rate of development of severe water stress. These leaf movements include drooping such as in a wilted sunflower, leaf rolling in grasses and orientation of the leaves parallel to the incoming radiation (Begg, 1980). The latter parahelionastic movement was also reported for grapevines (Vaadia & Kasimatis, 1961). Wilting of leaves and succulent shoots of grapevines in the sense of drooping, occur in containers or on shallow soils with a sudden rise in temperature (Kasimatis, 1967). Prolonged water stress in the field usually leads to necrosis of leaf edges and the dying of tendrils and shoot tips (Smart & Coombe, 1983). Continued water stress eventually leads to yellowing and shedding of basal leaves (Kasimatis, 1967; Van Zyl & Weber, 1977).

Many plant organs display diurnal shrinkage and swelling related to differences between the rate of water absorption and transpiration (Kozlowski, 1972). Vine trunks which can contain about 27% of the total water content of a grapevine (Smart & Coombe, 1983) and thus serve as important water storage organs, respond to the diurnal cycles of water status (Smart, 1974). Vaadia & Kasimatis (1961) used trunk circumference as a parameter to assess the final result of irrigation treatments. Trunk diameter of vines has not been used to determine the onset of water stress. Measurements of the stem diameter of cotton plants have been used by Huck & Klepper (1977) to estimate plant water potential.

Veihmeyer & Hendrickson (1957) regarded fruit growth to be the most sensitive indicator of water stress in the grapevine. Sensitivity of berry growth to water deficits during the first growth phase, which eventually leads to a reduction in yield even when stress is relieved, has been established by many researchers (Vaadia & Kasimatis, 1961; Hardie & Considine, 1976; Van Zyl & Weber, 1977). This may be associated with fewer cells per berry since cell division occurs in the pericarp during three weeks after flowering (Coombe, 1960; Harris, Kriedemann & Possingham, 1968; Coombe, 1976). During the lag and ripening phases of grapes, berries shrink and swell due to diurnal changes in water potential, but are no longer as sensitive to water stress as before (Smart & Coombe, 1983).

Root systems are generally less sensitive to water stress than other parts of the plant (Hofäcker, 1977; Düring, 1979; Kramer, 1983) and consequently roots are less suitable indicators of the onset of water stress. This may be due to more severe water deficits which persist longer in leaves and shoots and possibly also to more effective osmotic adjustment in roots than in shoots (Kramer, 1983). Allocation of assimilates also shifts towards the root. Root growth will therefore be less impaired by water stress than shoot growth. Mildly stressed plants can even increase their root growth. Consequently the plant can adapt itself to water stress over the longer term by a decrease in shoot : root ratios (Oosterhuis, 1982; Kramer, 1983). In addition to reducing the rate of water use, this adaptation improves access to soil water (Begg, 1980).

Physiological Indicators of Water Stress

Many morphological responses to water stress are often associated with the response of the more sensitive underlying physiological processes (Oosterhuis, 1982).

Water Potential: Water potential (ψ) has gained wide acceptance as a fundamental measure of plant water status for various reasons. Water

potential is a measure of the free energy status of water in plant tissue as well as in the soil and in solutions and it can be related to atmospheric moisture by the following equation (Salisbury & Ross, 1978) :

$$\psi = -\frac{RT}{V} \ln P_{o/p}$$
$$= -10,6 \; T \; \log_{10} \frac{(100)}{RH}$$

where,

ψ = water potential (bar)

R = universal gas constant (1 bar/mol deg.)

T = absolute temperature (°k)

V = partial molal volume of water (1/mol)

P_0 = vapour pressure of pure water at temperature T (mm Hg)

P = vapour pressure under test conditions (mm Hg)

RH = relative humidity (%)

Furthermore, water movement into and through plants occurs along gradients of decreasing ψ . Therefore measurements of ψ seem to have maximum application possibilities (Kramer, 1983). The availability of techniques employing thermocouple psychrometry (Slavik, 1974; Oosterhuis & Walker, 1982) and the Scholander pressure chamber (Scholander et al. 1965; Slavik, 1974) have led to the increased acceptance and use of ψ as an indicator of plant water status. Hsiao (1973) cautioned against the reliance on ψ as an indicator of physiological water stress because plant adaptation to the environment could affect the value of ψ at which stress sets in. Meyer & Green (1980) showed that predawn or covered ψ decreased rapidly in field-grown wheat in a lysimeter at the same time when evapotranspiration began to decrease (60 - 70% depletion of plant available water). These researchers prefer covered leaf water potential (LWP) for detection of onset of water stress because of the large day to day variation in exposed LWP (Meyer & Green, 1981).

Leaf water potential shows marked diurnal fluctuations (Smart & Barrs, 1973; Smart, 1974; Hardie & Considine, 1976; Liu et al., 1978a; Freeman, Lee & Turkington, 1980). Diurnal curves have been shown to be highly correlated with ambient radiation, temperature and saturation vapour deficit. Leaf water potential was linearly correlated with solar radiation up to midday (Smart & Barrs, 1973). Before dawn, LWP approaches equilibrium with soil water potential and reaches a maximum (least negative) daily value (Smart & Coombe, 1983).

Water potential has also been determined on inflorescences (Smart, 1974) and bunches (Liu et al., 1978a; Smart & Coombe, 1983). Water potentials of leaves and bunches were similar for non-irrigated vines throughout the day, but bunches on irrigated vines did not reach as low a minimum value as leaves. Leaves also recovered faster than bunches at night.

Hsiao et al. (1976) emphasized the fact that in using ψ reduction as an indicator of water stress a virtual absence of osmotic adjustment to the stress is assumed.

Stomatal Opening: Stomatal opening is affected by plant water deficits and can therefore be used as an indicator of water stress. However, stomatal behaviour is not affected by plant water status only, but also by other factors such as light, CO_2, humidity and temperature. Stomatal opening, transpiration and photosynthesis often decrease at the same rate in plants subjected to increasing water stress, although there is evidence that water stress which can cause stomatal closure and consequently a decline in CO_2 uptake, can also cause inhibition of CO_2 fixation through injury to the "photosynthetic machinery" (Kramer, 1983). The photosynthetic rate in Vitis leaves reaches a maximum when the water deficit is low, declines with increasing stress and recovers on rewatering (Höfacker, 1977; Smart & Coombe, 1983). It is further well documented that stomatal closure is the main

cause for a reduction in transpiration rate as water stress develops (Hsiao, 1973).

It is generally recognised that stomata do not respond to changes in LWP until a critical threshold value is reached and that the stomata close over a narrow range of ψ . This threshold value of ψ depends on plant species, plant age, plant history, leaf position and other environmental factors (Begg & Turner, 1976). Nevertheless it has been shown that stomata of potted as well as field grown Shiraz, close at -1 300 kPa (Kriedemann & Smart, 1971; Smart, 1974). Liu et al. (1978b) found stomatal closure of potted Concord at -1 300 kPa, but in a Concord vineyard the stomata remained open at -1 600 kPa.

The diffusion rate of water vapour from leaves is often measured by porometers calibrated to convert the readings into leaf resistance or conductance, generally referred to as stomatal resistance and stomatal conductance, respectively. The latter two parameters are closely related to stomatal aperture (Kramer, 1983). A few researchers related stomatal resistance to soil water status. Hofäcker (1976) found in potted plants a decrease in rate of photosynthesis and stomatal resistance at 50% and 60% of FC with the cultivars Oris and Müller Thurgau respectively. In another pot experiment Düring (1979) found an increase of stomatal resistance at 60% of FC. Soil water regimes of 30% and 40% of FC maintained in pots, reduced the rates of photosynthesis to 52% and 67% respectively and the transpiration rate to 43 and 55% (Alleweldt & Rühl, 1982). In the last three studies cultivars differed considerably in their response to limited water content. In lysimeter studies with Waltham Cross, Van Rooyen, Weber & Levin (1980) predicted an average soil water potential combination of -5,2 kPa before véraison and -3,9 kPa after véraison to ensure the minimum stomatal resistance. A good correlation (r > 0,90) between soil water potential and stomatal resistance was found during the two years of this study.

Vines bearing fruit have been shown to have lower stomatal resistances than non-bearing vines at the same water deficits, and stomatal resistance of grapevines under stress was inversely affected by changes in air humidity (Hofäcker, 1976). Well watered grapevines showed no response to changes in air humidity (Düring, 1976). It is thus evident that stomatal behaviour is affected by many external environmental factors as well as by internal factors.

Different enzymes are affected to varying degrees by water stress, nitrate reductase being very sensitive (Hsiao, 1973), but its usefulness as a stress indicator needs further investigation.

Abscicic acid (ABA) is less sensitive than nitrate reductase to water stress (Hsiao, 1973). Aspinall (1980) reported that ABA responds very rapidly to a "substantial fall in water potential" and can accumulate within minutes. Due to its rapid response ABA allows the plant to react dynamically to a constantly changing environment. The interest in stress-induced ABA accumulation centres on the effect of this growth regulator on stomatal opening. It has been shown for grapevines that ABA can increase sufficiently in stressed vines to induce stomatal closure (Smart & Coombe, 1983). This relationship between ABA and stomatal opening does not always hold true. After rewatering a stressed plant, stomatal opening often recovers slowly, while leaf ABA content returns to normal a considerable time before stomatal re-opening (Hsiao et al., 1976). The grapevine cultivar Sylvaner showed a corresponding poor correlation between ABA and stomatal resistance following water stress, but in the more drought resistant cultivar Riesling, a good correlation was found (Smart & Coombe, 1983).

Hsiao (1973) listed protein synthesis third in sensitivity to water stress after cell growth and cell wall synthesis. Despite its high sensitivity and rapid response to water stress, protein synthesis is not a practical indicator due to difficulties involved in the measurement techniques.

Accumulation of free proline as a result of water stress has been described for many plant species (Steward & Hanson, 1980), but no research has been done on vines in this respect. According to these authors, three main factors cause proline to accumulate under stress, viz.:

(1) Enhanced synthesis.

(2) Inhibited oxidation, probably due to effects on mitochondria.

(3) Impaired protein synthesis.

The level of free proline in stressed tissue is determined by the combined effect of these three factors as well as the rate of proline export via the phloem. Hsiao (1973) did not consider proline accumulation as a very sensitive indicator of water stress, but he does mention the possibility that proline accumulation may be beneficial to plants under stress. This was indicated by the positive correlation between proline accumulation in 10 barley varieties and their drought resistance ratings.

Leaf and Canopy Temperature

The use of canopy temperature as an indicator of water stress in crops has been suggested and investigated by many researchers (Tanner, 1963; Fuchs & Tanner, 1966; Wiegand & Namken, 1966; Ehrler, 1973; Idso, Jackson & Reginato, 1977; Ehrler et al., 1978; Sandhu & Horton, 1978; Jung & Scott, 1980; Berliner, Oosterhuis & Green, 1984). This theory is based on the fact that leaf temperatures will rise if water supply to the plant becomes limiting, resulting in stomatal closure, increase of diffusion resistance of the leaf and a drop in the transpiration rate (Gates, 1968). However, transpiration rate is not the only factor affecting leaf temperature.

Transpiration rate and leaf temperature are in fact dependent upon many independent climatic variables interacting with the plant (Gates, 1968). The climate and the leaf are linked to each other by the flow of energy. According to Gates (1964) this energy exchange for the steady state situation in the absence of photosynthesis can be expressed in the following equation:

$$a_s \ (S + s) + a_t \ (R_a + R_g) = R_l \pm C + LE$$

where,

a_s =   absorptivity of the plant to sunlight

a_t =   absorptivity of the plant to long wave thermal radiation

S =   incident direct solar radiation and skylight

s =   reflected sunlight from the ground

R_g =   incident thermal radiation from the ground

R_a =   incident thermal radiation from the atmosphere

R_l =   radiation from the leaf

C =   convection

LE =   transpiration

Some researchers have consequently cautioned against using temperature as a stress-indicator unless concurrent measurements of air temperature, vapour pressure, radiation and wind speed are also taken (Idso, Jackson & Reginato, 1977; Ehrler et al., 1978). The largest effect of transpiration on leaf temperature is found under windless conditions. An increase of wind speed firstly decreases the resistance in the transpiration pathway by reducing the thickness of the adhering boundary layer of air around the leaf and secondly changes the leaf temperature by forced convection (Gates, 1968). In a recent study on wheat, Berliner, Oosterhuis & Green (1984) found that

changes in canopy temperature were clearly associated with changes in wind speed. They ascribed this temperature change mainly to canopy cooling.

Actual air temperature also affects leaf temperature. Measurements made in a growth chamber on several plant species indicated that plants become cooler than the ambient air between an air temperature of 30 to 40°C, but below these temperatures leaves were warmer than the air. With increasing leaf temperature the stomatal resistance will decrease and consequently lower leaf temperatures would result at high air temperatures (Gates, 1968). He reported a sudden drop in total leaf resistance at a leaf temperature of 41°C leading to increased transpiration. Gates (1968) calculated that a transpiring leaf can be 10°C cooler than a non-transpiring leaf at an air temperature of 40°C. He came to the conclusion that the ability to transpire will make a substantial difference in leaf temperature when the heat load on a leaf is large.

Early attempts to measure leaf temperatures when mainly contact sensors e.g. thermocouples were used, were hampered by difficulties such as variation in leaf exposure and sampling problems when plant canopies were to be studied (Tanner, 1963; Fuchs & Tanner, 1966). Many of these problems were overcome with the development of remote sensing of surface temperatures through thermal radiation measurements, utilising the direct relationship between the surface temperature of an object and emitted electromagnetic radiation (Tanner, 1963; Fuchs & Tanner, 1966; Wiegand & Namken, 1966; Aston & Van Bavel, 1972; Idso, Jackson & Reginato, 1977). Since 1980, studies in which infrared thermometers were used to determine canopy temperature have increased in number (Jung & Scott, 1980; Gardner, Blad & Watts, 1981; Jackson et al. 1981; Scott, Jung & Ferguson, 1981; Clawson & Blad, 1982; Berliner, Oosterhuis & Green, 1984; Bonanno & Mack, 1983; Mottram, De Jager & Duckworth, 1984).

Several indices for the prediction of crop water stress from the crop canopy temperature have been proposed and tested, and will be treated below.

Spatial Variability of Canopy Temperature within a Field: This method, first suggested by Aston & Van Bavel (1972), was used to relate large midday spatial variability in canopy temperature of maize to water stress (Gardner & Blad, 1980; Gardner, Blad & Watts, 1981). They concluded that a standard deviation above ± 0,3°C signals water stress. In a follow-up study Clawson & Blad (1982) defined canopy temperature variability (CTV) as the range (maximum minus minimum) of canopy temperatures sensed with the infra-red thermometer during a particular measurement period. They suggest the onset of water stress in maize when CTV values exceed 0,7°C. Berliner, Oosterhuis & Green (1984) question the use of this method in view of the effect of changing wind speed. The variability of canopy temperature for a non-stressed plant on "gusty days" is higher than for a stressed plant on a quieter day.

Canopy/Air Temperature Differences ($\triangle$ T):   Detection of water stress by this method is based on the fact that midday canopy temperatures of a well watered plant remain 2 to 7°C below air temperature, but as water supply to the plant becomes limiting, canopy temperatures increased to 2 to 4°C above air temperature (Wiegend & Namken, 1966; Ehrler, 1973; Jackson, Reginato & Idso, 1977; Sandhu & Horton, 1978; Jung & Scott, 1980). Jackson, Reginato & Idso (1977) verified $\triangle$ T = 0 as indicator of water stress in wheat and this value was also used by Ehrler et al. (1978) for wheat. However, Gardner, Blad & Watts (1981) found with maize that $\triangle$T remained negative despite stress conditions. Ehrler (1973) suggested the use of leaf temperature minus air temperature ($\triangle$T) to schedule irrigations, provided that the following precautionary steps are taken:

(1) Temperature measurements must be well-replicated and standardized.
(2)   Saturation deficits must be known in order to supply a correction factor to $\triangle$ T if necessary.
(3) Species differences are taken into account.

The stress-induced increase of leaf temperature above canopy temperature were further standardized when Idso, Jackson & Reginato (1977) devised the stress degree day (SDD) concept in which the final yield of a crop (Y) is hypothesised to be linearly related to total SDD accumulated over a critical period:

$$Y = \alpha - \beta \left(\sum_{i=b}^{e} SSD \right)$$

where,

α, β = linear relationship constants

SDD   = mid-afternoon (14h00) leaf temperature - air temperature on day i.

b, e   = respective days on which the summation procedure is to begin and end.

With the aim at scheduling irrigations the SDD is defined as follows (Jackson, Reginato & Idso, 1977) :

$$SDD = \sum_{n=i}^{N} (Tc - Ta) \, n$$

where,

Tc = crop canopy temperature at midday (°C)

Ta = air temperature 1,50m above soil surface at midday (°C)

N = number of days beginning with day i.

The SDD concept of yield prediction was proved to be basically sound for wheat (Idso, Jackson & Reginato, 1977).

In a study to evaluate the SDD concept for snapbeans Bonanno & Mack (1983) scheduled irrigations with the aid of an infrared thermometer. They found that SDD accumulation was more rapid when maximum temperatures were between 20°C and 30°C than during temperature extremes near 40°C. They overcame this problem by plotting air vapour pressure deficit against SDD values for a well-watered crop and by using this regression line to "correct" the temperatures. This method ensured positive SDD accumulation under any environmental condition.

Shortcomings of the SDD concepts were overcome when Idso et al. (1981a) defined a crop water stress index (CWSI) to account for the dependency of ΔT on the vapour pressure deficit in the air. This index was based upon the discovery that a plot of ΔT versus air vapour pressure deficit yields a straight line which is unique for every specific crop during the greater part of the daylight period, provided that the plants are exposed to full sun and no water deficits exist i.e. that the plant transpires at the maximum rate possible under the prevailing meteorological conditions. This line serves as the lower limit at which no water stress exists. Idso (1982) experimentally determined such non-water-stressed baselines for 26 different plant species, mostly field crops, employing infrared measurement of foliage temperature and psychrometric measurement of the vapour pressure deficit of the air. Idso et al. (1981a) also determined an upper limit to hold for non-transpiring plants i.e. for a situation where the vapour pressure gradient between air and foliage is zero. This upper limit is strongly temperature dependent. The CWSI for a set of data points located at point P (see graphic presentation below) is defined as (Idso, et al., 1981a; Idso, Reginato & Farah, 1982) :

CWSI = c/d

where,

c = vertical distance between P and the lower limit (maximum transpiration).

d = vertical distance at point P between upper limit (no transpiration) and lower limit.
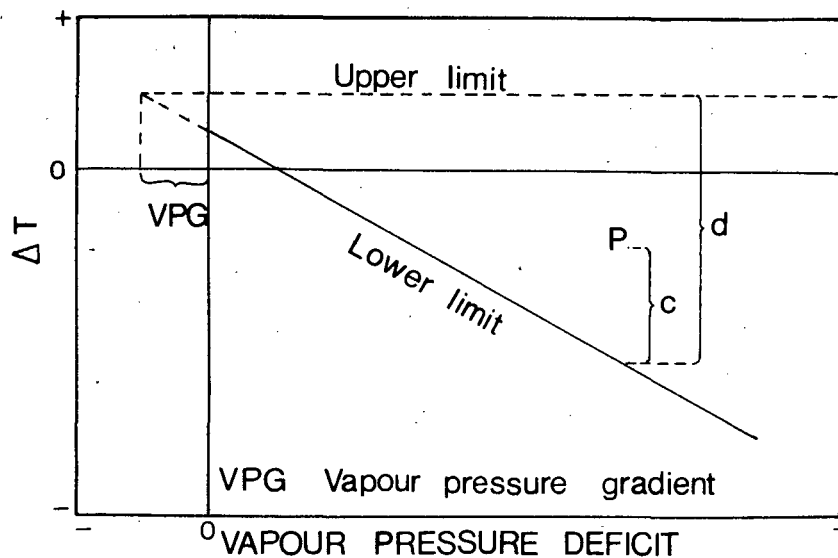
This new index has already been related to soil water content (Jackson, et al. 1981), plant water potential (Idso et al., 1981b,c) leaf diffusion resistance and photosynthesis (Idso et al., 1982) and the ratio of actual to potential evapotranspiration (Mottram, De Jager & Duckworth, 1984). Idso, Reginato & Farah (1982) estimated the quantity of extractable water remaining in the soil using the CWSI. They concluded that the CWSI is a sensitive index of soil and plant water status and can be used to separate total plant water potential into atmospheric and soil induced components.

Canopy Temperature vs. that of a Reference Plot: An alternative approach was used by various researchers who compared the measured canopy temperature to that of a reference non-stressed plot (Tanner, 1963; Fuchs & Tanner, 1966; Sandhu & Horton, 1978; Gardner, Blad & Watts, 1981; Berliner, Oosterhuis & Green, 1984). In this way the interference of confounding factors such as changing atmospheric conditions and additional measurements can be avoided. Temperature differences between stressed and non-stressed leaves reported for various crops ranged from +2 to +8°C (Gardner, Blad & Watts, 1981). In a most recent study Berliner, Oosterhuis & Green (1984) found this index most promising despite practical problems posed by the

maintenance of a reference (well-watered) plot. They also reported that the scatter of observations was comparable to that obtained when more complex approaches involving additional routine measurements were used.

Scott, Jung & Ferguson (1981) found a linear relationship between canopy temperature and LWP for both irrigated and unirrigated soybeans. Linear relationships were also found between the canopy temperature difference and leaf water potential difference ($\triangle$ LWP) as well as between canopy temperature difference ($\triangle$CT) and stomatal resistance difference ($\triangle$Rs) when stressed wheat were compared to a reference plot (Berliner, Oosterhuis & Green, 1984). They reported onset of stress at a $\triangle$LWP between the stressed and a well watered plot of around 500 kPa which indicated a $\triangle$CT of 2,8°C. At present, calibration of the stressed/reference temperature differentials for the different crops seem to be the most serious problem to overcome before this method can be used to determine onset of stress and for the scheduling of irrigation.

It is clear from the above discussion that a great number of different plant morphological and physiological parameters are affected by water stress. Relationships among these parameters and their relationship with soil water status and evapotranspiration have to be investigated further for grapevines specifically to find the most correct and practical way of timing irrigations and prevent adverse water deficits in the plant. In order to eliminate meteorological variables and determine vine response to a change in soil water status only, the first investigation in a series of pot and field experiments was conducted in a glasshouse. This experiment aimed at determining the onset of water stress with regard to various plant morphological and physiological parameters.

MATERIALS AND METHODS

Colombar vines (Clone 2/1154) were planted in 50 dm^3 earthenware pots, two of which were filled with the sandy soil (10,5% coarse sand; 45,5% medium sand; 37,4% fine sand; 5,6% silt; 0,0% clay) also used in the auto-irrigation trial (see Chapter 3) and two filled with a sandy clay loam (2,4% coarse sand; 11,4% medium sand; 49,9% fine sand; 12,0% silt; 21,7% clay) on which a field trial (see Chapter 4) was carried out. Vines were allowed to establish for one season out of doors at -20 kPa soil water regime. During the second season these vines were placed in a glasshouse at 26°C and a 60-70°C relative humidity a few weeks before the trial commenced. The last irrigation was applied on the 1st December (growth phase between flowering and véraison) and the pots were then left to dry while plant response was monitored regularly during the drying cycle.

Soil water content was determined by tensiometers installed at two depths viz., 0,18 m and 0,36 m in the pots, but when the soil water potential decreased below -75 kPa, small soil samples were taken in triplicate at the two specified depths for gravimetric determination of soil water content. Shoot lengths as well as the leaf angle between leaf blade and petiole as described by Smart (1974) were determined on four representative shoots and leaves on each vine respectively. Copper-Constantan thermocouples firmly attached to the abaxial side of four leaves per vine were used to measure leaf temperature. Changes in trunk diameter were determined using dial gauges screwed into the vine trunks.

The physiological response of grapevines to water stress was assessed through determination of LWP with the aid of a pressure chamber, Rs using an automatic diffusion porometer (manufacturer: Crump Scientific) and by measuring photosynthesis. The photosynthetic rate was determined in terms of CO_2 uptake with the aid of a portable field apparatus designed by Shimshi (1969). These plant physiological measurements were carried out on two leaves per vine and the same leaves were always used for the determination of all three parameters. All measurements were repeated twice on measurement days, viz., at 10h00 - 11h00 and at 14h00 - 15h00.

Curve-fitting was done with a statistical programme developed by Daniel & Wood (1971) in order to quantity the relationships between the soil water status and plant physiological parameters. Data for the two soils were analysed separately.

RESULTS AND DISCUSSION

Plant response to water stress was reflected in all measured parameters, but measurement techniques were not equally successful and the plant processes differed in their sensitivity to soil water depletion.

Plant Morphological Indicators of Water Stress

Shoot elongation was the most sensitive indicator of decreasing soil water potential (Figs. 1, 2 & 3) and, irrespective of soil type, decreased continuously until it stopped altogether on the sixth day at soil water potentials approaching -80 kPa. The decrease in shoot elongation rate commenced as soon as the soil water potential fell below the field capacity value (Fig. 1). This finding is in agreement with the review of Hsiao (1973) which listed cell growth as the most sensitive plant indicator of water stress.

Due to plant growth, trunk diameter increased and acquired a maximum on the fifth and seventh day for the sand (Fig. 2) and the sandy clay loam (Fig. 3) respectively. These maximum values coincided well with termination of shoot elongation. Thereafter trunk diameter decreased almost linearly with the progressive increase of plant water stress as the soil dried out.

Leaf angle was less sensitive to water stress than other morphological factors and did not show clear drought symptoms until the 12th day (Fig. 2 & 3), but wilting of the shoot tips and a few green berries were already visible at that stage. The older leaves on vines in the sand started to yellow rapidly on the 12th day while those of vines in the sandy clay loam followed suit three days later. The rapid yellowing and shedding of the older leaves can be seen as a method of drought adaptation by diminishing the leaf area and thus the transpirational water loss. Yellowing of leaves and the increase in leaf angle coincided with attainment of PWP in the soil. The soils dried to water contents below PWP (Fig. 2 & 3), but it is not clear whether soil water loss below PWP was only due to evaporation or also to water extraction by vine roots.

Plant Physiological Water Stress Indicators

Leaf water potential decreased gradually with decreasing soil water content (Fig. 2 & 3). The lowest LWP recorded was -2 100 kPa at a stage when the vines had already lost most of their leaves and the water content of the sandy clay loam was at 1,2% below PWP. Statistically significant curvilinear relationships were found between soil water content and LWP on both the sandy soil (R^2 = 0,67) (Fig. 4) and the sandy clay loam (R^2 = 0,71) (Fig. 5). The shapes of these curves bear a strong resemblance to the soil water release curves of these two particular soils viz., rapid decrease in soil water potential with decreasing soil water content on the sandy soil (Chapter 3; Fig. 4) in comparison to a more gradual decrease of soil water potential on the sandy clay loam (Chapter 5; Fig. 7).

Stomatal resistance started to increase at about the same time when shoot elongation and trunk growth stopped (Fig. 2 & 3). The relationships between Rs and soil water contents of the sandy soil and the sandy clay loam are illustrated in Figs. 6 & 7 respectively. These curvilinear relationships (R^2 = 0,89 sand; R^2 = 0,76 sandy clay loam) showed that the stomata remained open until the soil water contents of both soils had decreased considerably. On the sand, stomatal closure commenced at a soil water content of approximately 6% i.e. 27% total available water or a soil water potential of only -11 kPa. The rate of increase in stomatal closure with decreasing soil water status was, however, rapid and total stomatal closure occurred at a water content of 3,5% (soil water potential = -1000 kPa).

Stomatal closure on the sandy clay loam soil (Fig. 7) started later (soil water content = 15,5% i.e. 65% total available water or a soil water potential of -23 kPa), but proceeded more gradually than on its counterpart. The stomata were completely closed at a soil water content of 12% (-850 kPa). The stomatal resistance vs. soil water content curves (Figs. 5 & 6) again strongly resembled the soil water release curves for these two particular soils, suggesting that the stomatal behaviour of the grapevines is a function of the soil water potential when other environmental conditions are constant.

The relationships between LWP and Rs in this pot experiment are illustrated in Figs. 8 & 9. The onset of water stress as indicated by an increase in Rs occurred between -900 and -1 000 kPa on both soils. Stomatal resistance did not change much until this threshold value of LWP had been reached.

Photosynthetic rate declined in correspondence to drying of the soil and increasing stomatal resistance (Figs. 2 & 3). A low rate of CO_2 uptake continued even after the soil had reached PWP. In this study photosynthesis

held no advantage over stomatal opening as regards sensitivity to water stress.

The temperature differential between leaves and the ambient air was not a very successful indicator of plant water stress due to problems with the contact sensors. There was, however, a general tendency for the leaves to become warmer relative to the ambient air. Canopy temperature of grapevines as a water stress indicator was consequently further investigated in a vineyard by infrared thermometry in a later study (see Chapter 7).

CONCLUSION

Shoot elongation of non-bearing grapevines provided a very sensitive indicator of water stress. No abrupt change from non-stressed to stressed growth occurred, but shoot growth decreased continuously between field water capacity and -80 kPa at which it stopped completely. Trunk growth as indicated by an increase in trunk diameter stopped at the same time as shoot elongation. A decrease in trunk diameter was associated with decreasing soil water status.

Plant physiological parameters i.e. LWP and Rs were highly significantly correlated with soil water content. These curvilinear relationships resembled the soil water release curves of the two soils investigated. A comparison between these soils with regard to the onset of water stress once again emphasized the danger of comparing the effect of different soil water contents without relating it to soil water potential. Stomatal closure started at 27% total available water on the sand, but already at 65% total available water on the sandy clay loam. These water contents represented soil water potentials which were not that much different viz., -11 and -23

kPa respectively. This phenomenon makes it impossible to quantitatively interpret or extrapolate results obtained in other studies which related plant parameters to soil water content (Hofäcker, 1976; Düring, 1979; Alleweldt & Rühl, 1982) without supplying soil water content or soil water potential data for the soil.

In this experiment grapevine stomata remained open until a threshold LWP of -900 to - 1 000 kPa was attained. This threshold LWP was higher than the -1 300 kPa reported in literature. The difference is probably due to glasshouse conditions which prevailed in the present experiment, although the cultivar may also have contributed to the result.

Photosynthesis decreased, and air temperature/leaf temperature differentials increased with decreasing soil water potential. Results obtained in this study should be interpreted in conjunction with results of the field experiment (Chapter 6).

LITERATURE CITED

ALLEWELDT, G. & RüHL, E., 1982. Untersuchungen zum Gaswechsel der Rebe. II. Einfluss langanhaltender Bodentrocknheit auf die Leistungsfähigkeit verschiedener Rebsorte. *Vitis* 21, 313-324.

ASPINALL, D., 1980. Role of abscisic acid and other hormones in adaptation to water stress. In : N.C. Turner & P.J. Kramer (eds.). Adaptation of plants to water and high temperature stress. John Wiley & Sons, New York, pp. 155-172.

ASTON, A.R., & VAN BAVEL, C.H.M., 1972. Soil surface water depletion and leaf temperature. *Agron. J.* 64, 368-373.

BEGG, J.E., 1980. Morphological adaptations of leaves to water stress. In : N.C. Turner & P.J. Kramer (eds.). Adaptation of plants to water and high temperature stress. John Wiley & Sons, New York, pp. 33-42.

BEGG, J.E., TURNER, N.C., 1976. Crop water deficits. *Adv. Agron.* 28, 161-217.

BERLINER, P., OOSTERHUIS, D.M. & GREEN, G.C., 1984. Evaluation of the infrared thermometer as a crop stress indicator. *Agric. Forest. Meteor.* 31, 219-230.

BONANNO, A.R. & MACK, H.J., 1983. Use of canopy-air temperature differentials as a method for scheduling irrigations in snap beans. *J. Amer. Soc. Hort. Sci.* 108, 826-831.

CLAWSON, K.L. & BLAD, B.L., 1982. Infra-red thermometry for scheduling irrigation of corn. Agron. J. 74, 311-316.

COOMBE, B.G., 1960. Relationship of growth and development to changes in sugars, auxins and gibberelins in fruit of seeded and seedless varieties of Vitis vinifera. Plant Physiol. 35, 241-250.

COOMBE, B.G., 1976. The development of fleshy fruits. Ann. Rev. Plant. Physiol. 27, 507-528.

DANIEL, C. & WOOD, F.S., 1971. Fitting equations to data. Wiley Interscience, New York and London.

DüRING, H., 1976. Untersuchungen zur Umweltabhängigkeit der stomatären Transpiration bei Reben. I. Beleuchtungsstärke und Luftfeuchtigkeit. Vitis 15, 82-87.

DüRING, H., 1979. Wirkungen der Luft- und Bodenfeuchtigkeit auf das vegetative Wachstum und der Wasserhaushalt bei Reben. Vitis 18, 211-220.

EHRLER, W.L., 1973. Cotton leaf temperatures as related to soil water-depletion and metereological factors. Agron. J. 65, 404-409.

EHRLER, W.L., IDSO, S.B., JACKSON, R.D. & REGINATO, R.J., 1978. Wheat canopy temperature : Relation to plant water potential. Agron. J. 251-256.

EIBACH, R. & ALLEWELDT, G., 1983. Einfluss der Wasserversorgung auf Wachstum, Gaswechsel und Substanzproduktion traubentragender Reben. I. Das vegetative Wachstum. *Vitis* 22, 231 - 240.

FREEMAN, B.M., LEE, T.H. & TURKINGTON, C.R., 1980. Interaction of irrigation and pruning level on grape and wine quality of Shiraz vines. *Am. J. Enol. Vitic.* 31, 124-135.

FUCHS, M. & TANNER, C.B., 1966. Infrared thermometry of vegetation. *Agron. J.* 58, 597-601.

GARDNER, B.R. & BLAD, B.L., 1980. Plant and canopy temperatures in corn as influenced by differential moisture stress. *Agric. Meteorol.* Progress. Report 80-1, Center for Agricultural Meteorology and Climatology, Univ. of Nebraska-Lincoln. 119 p.

GARDNER, B.R., BLAD, B.L. & WATTS, D.G., 1981. Plant and air temperatures on differentially irrigated corn. *Agric. Metereol.* 25, 207-217.

GATES, D.M., 1964. Leaf temperature and transpiration. *Agron. J.* 56, 273-277.

GATES, D.M., 1968. Transpiration and leaf temperature. *Ann. Rev. Plant. Physiol.* 19, 211-238.

HARDIE, W.J. & CONSIDINE, J.A., 1976. Response of grapes to water deficit stress in particular stages of development. *Am. J. Enol. Vitic.* 27, 55-61.

HARRIS, J.M., KRIEDEMANN, P.E. & POSSINGHAM, J.V., 1968. Anatomical aspects of grape berry development. *Vitis* 7, 106-119.

HENSLEY, M., 1980. A comparison of two methods for determining plant available water in a soil profile. *Agrochemophysica* 12, 39-43.

HENSLEY, M. & DE JAGER, J.M., 1978. A technique for the determination of the available water capacity of a soil profile. Paper presented at the 8th Congress of the Soil Science society of Southern Africa 10-14th July, Pietermaritzburg.

HOFäCKER, W., 1976.   Untersuchungen über den Einfluss wechselnder Bodenwasserversorgung auf die Photosyntheseintensität und den Diffusionwiderstand bei Rebblättern. Vitis 15, 171-182.

HOFäCKER, W., 1977.   Untersuchungen zur Stoffproduktion der Rebe under dem Einfluss wechselnder Bodenwasserversorgung.   Vitis 16, 162-173.

HSIAO, T.C., 1973.   Plant responses to water stress. Ann. Rev. Plant Phys. 519-570.

HSIAO, T.C., ACEVEDO, E., FERERES, E. & HENDERSON, D.W., 1976. Stress metabolism.   Water stress, and osmotic adjustment. Phil. Trans. R. Soc. London. B. 273, 479-500.

HUCK, M.G. & KLEPPER, B., 1977. Water relations of cotton. II. Continuous estimates of plant water potential from stem diameter measurements. Agron. J. 69, 593-597.

IDSO, S.B., 1982. Non-water-stressed baselines : A key to measuring and interpreting plant water stress. Agric. Metereol. 27, 59-70.

IDSO, S.B., JACKSON, R.D., PINTER, Jr., P.J., REGINATO, R.J. & HATFIELD, J.L., 1981a.   Normalizing the stress-degree-day

parameter for environmental variability. Agric.Meteorol. 24, 45 - 55.

IDSO, S.B., REGINATO, R.J., REICOSKY, D.C. & HATFIELD, J.L., 1981b. Determining soil-induced plant water potential depressions in alfalfa by means of infrared thermometry. Agron. J. 73, 826-830.

IDSO, S.B., REGINATO, R.J., JACKSON, R.D. & PINTER, Jr., P.J., 1981c. Measuring yield-reducing plant water potential depressions in wheat by infrared thermometry. Irrig. Sci. 2, 205-212.

IDSO, S.B., JACKSON, R.D. & REGINATO, R.J., 1977. Remote-sensing of crop yields. Science 19 - 25.

IDSO, S.B., REGINATO, R.J. & FARAH, S.M., 1982. Soil- and atmosphere-induced plant water stress in cotton as inferred from foliage temperatures. Water Resources Res. 18, 1143 - 1148.

IDSO, S.B., REGINATO, R.D. & RADIN, J.W., 1982. Leaf diffusion resistance and photosynthesis in cotton as related to a foliage temperature based plant water stress index. Agric. Meteorol. 27, 27-34.

JACKSON, R.D., IDSO, S.B., REGINATO, R.J. & PINTER, Jr., P.J., 1981. Canopy temperature as a crop water stress indicator. Water Resources Res. 17, 1133-1138.

JACKSON, R.D., REGINATO, R.J. & IDSO, S.B., 1977. Wheat canopy temperature : A practical tool for evaluating water

requirements. Water Resources Res. 13, 651 - 656.

JUNG, P.K. & SCOTT, H.D., 1980. Leaf water potential, stomatal resistance, and temperature relations in field-grown soybeans. Agron.J. 72, 986 - 990.

KASIMATIS, A.N., 1967. In: R.M. Hagan, H.R. Haise & T.W. Edminister (eds.) Irrigation of agricultural lands. Agron. Series 11, 719 - 739. Am. Soc. Agron., Madison, Wisconsin.

KRAMER, P.J., 1969. Plant and soil water relationships : A modern synthesis. McGraw-Hill, New York.

KRAMER, P.J. 1983. Water relations of plants. Academic Press, New York.

KRIEDEMANN, P.E. & SMART., R.E., 1971. Effects of irradiance, temperature and leaf water potential on photosynthesis of vine leaves. Photosynthetica 5, 6-15.

KOZLOWSKI, T.T., 1972. Shrinking and swelling of plant tissue. In : T.T. Kozlowski (ed.). Water deficits and plant growth III. Academic Press, New York, pp. 1-64.

LIU, W.T., WENKERT, W., ALLEN, L.H. & LEMON, E.R., 1978a. Soil-plant water relations in a New York vineyard : Resistances to water movement. J. Amer. Soc. Hort. Sci. 103, 226-230.

LIU, W.T., POOL, R., WENKERT, W. & KRIEDEMANN, P.E., 1978b. Changes in photosynthesis, stomatal resistance and abscisic acid of Vitis Labruscana through drought and irrigation cycles. Am. J. Enol. Vitic. 29, 239-246.

MEYER, W.S. & GREEN, G.C., 1980. Water use by wheat and plant

indicators of available soil water. Agron. J. 72, 253 - 257.

MEYER, W.S. & GREEN, G.C., 1981. Plant indicators of wheat and soybean crop water stress. Irrig.Sci. 2, 169 - 176.

MOTTRAM, R., DE JAGER, J.M. & DUCKWORTH, J.R., 1984. Evaluation of a water stress index for maize using an infrared thermometer. S. Afr. J. Plant Soil. 1(4), in press.

OOSTERHUIS, D.M., 1982. Physiological and morphological indicators of crop water stress. Workshop on agronomic aspects of irrigation research, March 1 - 3, 1982. Co-ordinating Committee for Irrigation Research, Dept. of Agriculture, Pretoria.

OOSTERHUIS, D.M. & WALKER, S., 1982. Field measurements of leaf water potential components using thermocouple psychrometers : I. Techniques. Crop. Prod. 11, 1-4.

SALISBURY, F.B. & ROSS, C.W., 1978. Plant physiology (2nd ed.) Wadsworth Publishing Company, Belmont, California.

SANDHU, B.S. & HORTON, M.L., 1978. Temperature response of oats to water stress in the field. Agric. Meteorol. 19, 329-336.

SCHOLANDER, P.F., HAMMEL, H.T., BRADSTREET, E.D. & HEMMINGSEN, E.A., 1965. Sap pressure in vascular plants. Science 148, 339-346.

SCOTT, H.D., JUNG, P.K. & FERGUSON, J.A., 1981. A comparison of soybean leaf water potential and leaf temperature under progressive drought. Agron.J. 73, 574 - 576.

SHIMSHI, D., 1969. A rapid field method for measuring photosynthesis with labelled carbon dioxide. J. Exp. Bot. 20, 381 - 401.

SLATYER, R.O., 1967. Plant water relationships. Academic Press, New York.

SLAVIK, B., 1974. Methods of studying plant water relations. Ecological Studies 9. Springer-Verslag, Berlin and New York.

SMART, R.E., 1974. Aspects of water relations of the grapevine (Vitis vinifera). Amer. J. Enol. Vitic. 25, 84 - 91.

SMART, R.E. & BARRS, D., 1973. The effect of environment and irrigation intervals on leaf water potential of four horticultural species. Agric. Meteorol. 12, 337 - 346.

SMART, R.E. & COOMBE, B.G., 1983. Water relations of grapevines. In: T.T. Kozlowski (ed.) Water dificits and plant growth VIII. Academic Press, New York, pp. 137-196.

STEWARD, C.R. & HANSON, A.D., 1980. Proline accumulation as a metabolic response to water stress. In : N.C. Turner & P.J. Kramer (eds.) Adaptation of plants to water and high temperature stress. Wiley, New York, pp. 173-189.

TANNER, C.B., 1963. Plant temperatures. Agron. J. 55, 210-211.

VAADIA, Y. & KASIMATIS, A.N., 1961. Vineyard irrigation trials. Am. J. Enol. Vitic. 12, 88-98.

VAN ZYL, J.L., 1981. Waterbehoefte en besproeiing. In : J.D. Burger & J. Deist (eds). Wingerdbou in Suid-Afrika. VORI, Stellenbosch, South Africa, pp. 234-282.

VAN ZYL, J.L. & KENNEDY, C.S., 1983. Vine response to water stress induced by polyethylene glycol. S. Afr. J. Enol. Vitic. 4, 1-5.

VAN ZYL, J.L. & WEBER, H.W., 1977. Irrigation of Chenin blanc in the Stellenbosch area within the framework of the climate-soil-water-plant-continuum. Proc. Int. Symp. on the Quality of the Vintage, 14-21 Feb. 1977, Cape Town.

VAN ROOYEN, F.C., WEBER, H.W. & LEVIN, I., 1980. The response of grapes to a manipulation of the soil-plant-atmosphere continuum. II Plant-water relationships. Agrochemophysica 12, 69-74.

VEIHMEYER, F.J. & HENDRICKSON, A.H., 1957. Grapes and deciduous fruits. Irrigation of deciduous orchards and vineyards influenced by plant-soil-water relationships in individual situations. Calif. Agric. 11 (4), 13-18.

WIEGAND, C.L. & NAMKEN, L.N., 1966. Influences of plant moisture stress, solar radiation, and air temperature on cotton leaf temperature. Agron.J. 58, 582 - 586.
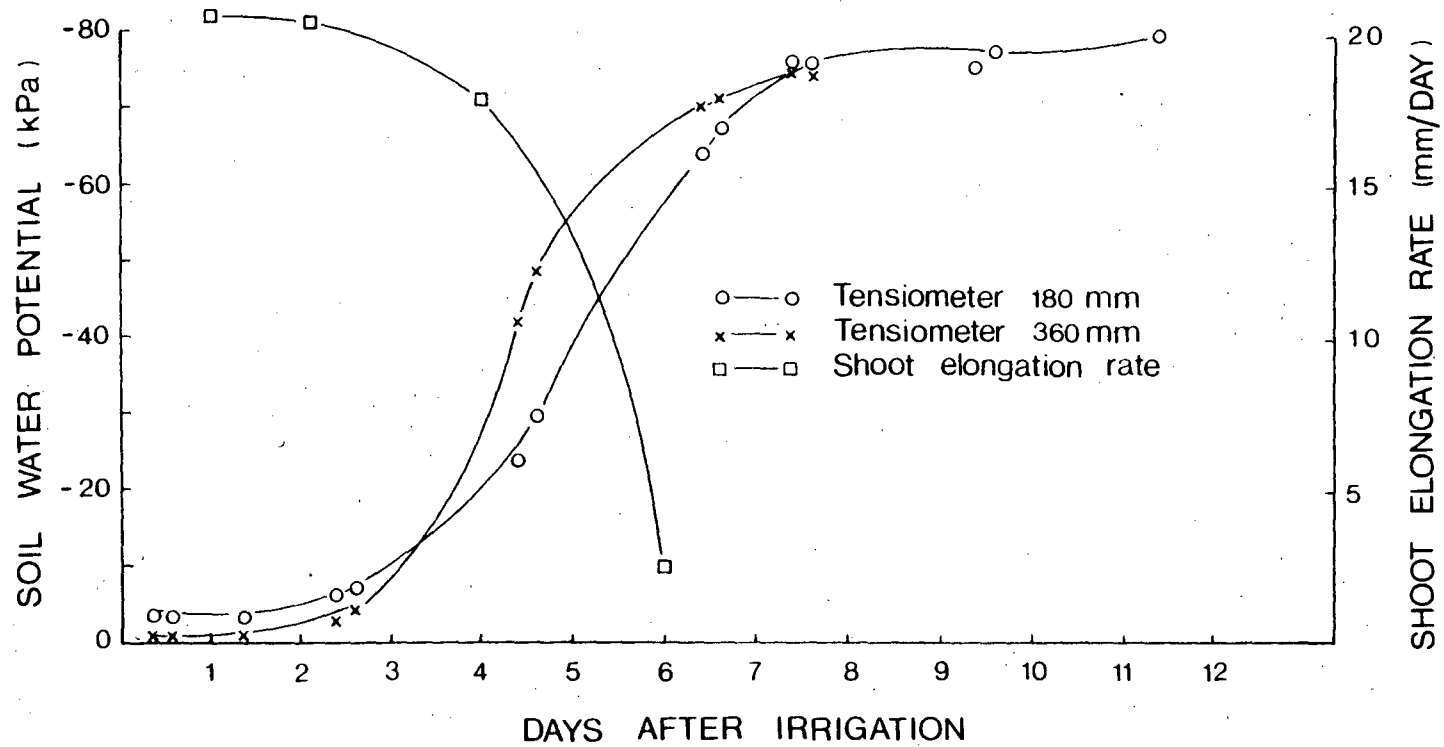
Fig. 1:   Decrease in shoot elongation rate of Colombar/99R as a result of the decrease
in soil water potential of a sandy soil.
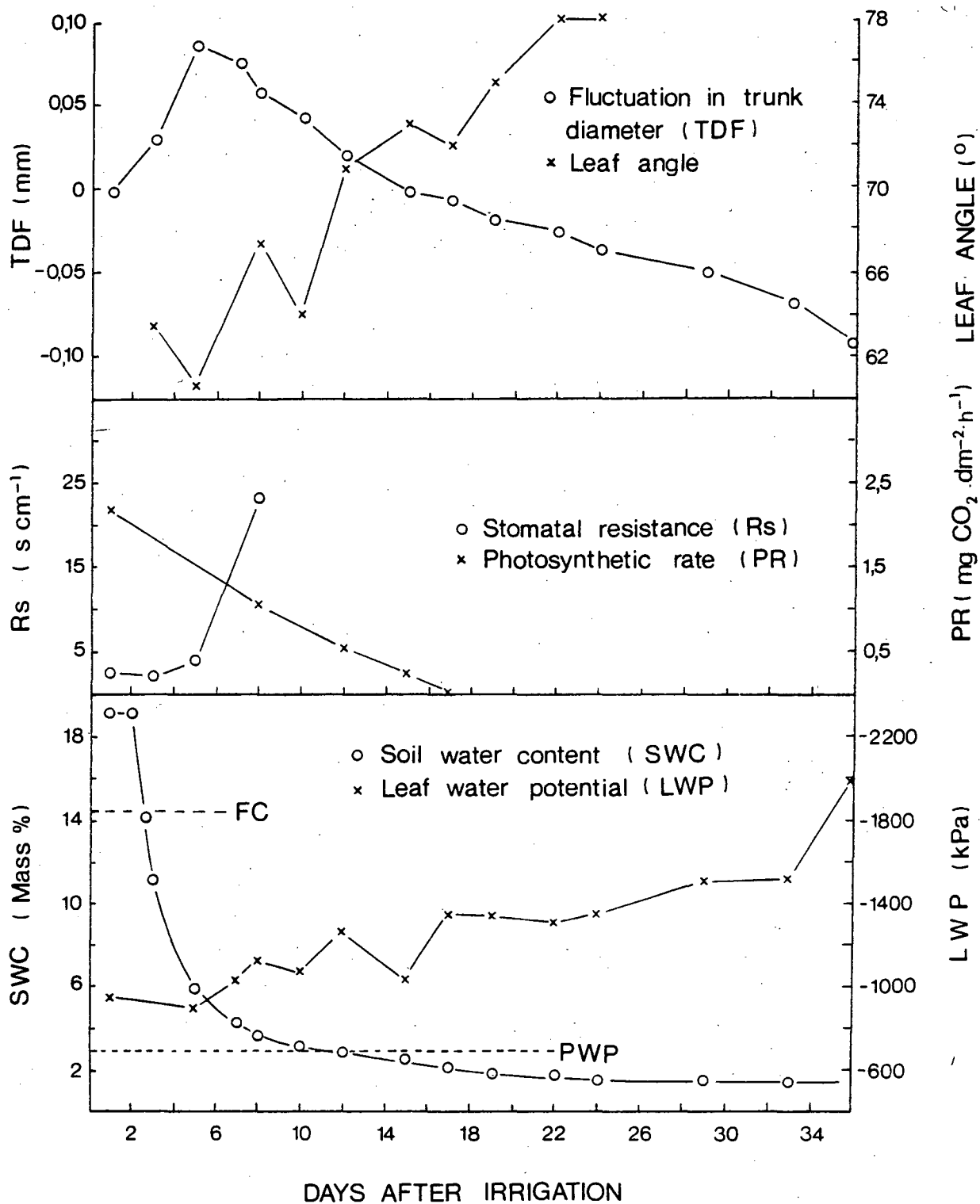
Fig. 2: Morphological and physiological responses of grape-
vines during a drying cycle in sandy soil.
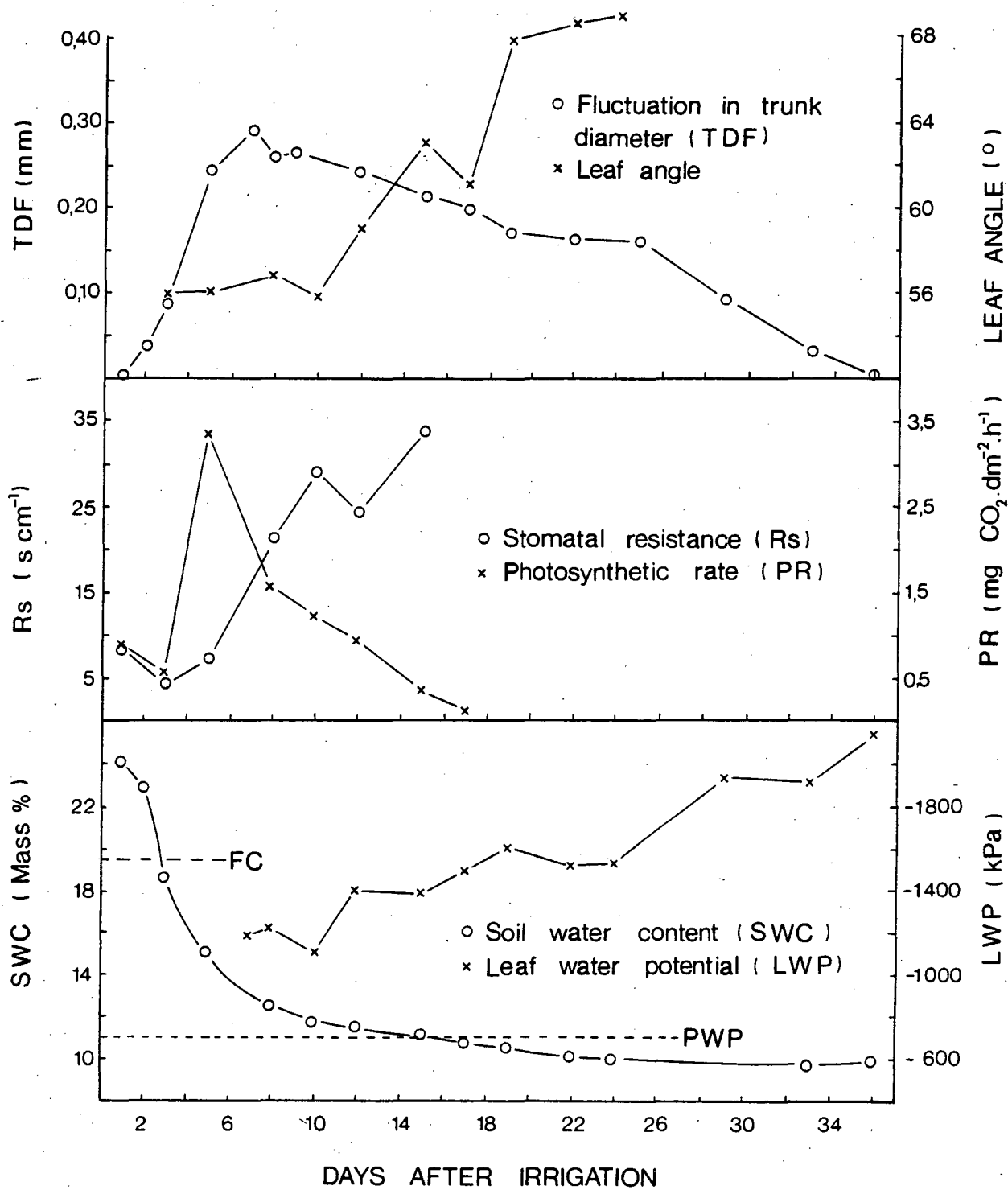
Fig. 3: Morphological and physiological responses of grapevines during a drying cycle in a sandy clay loam soil.
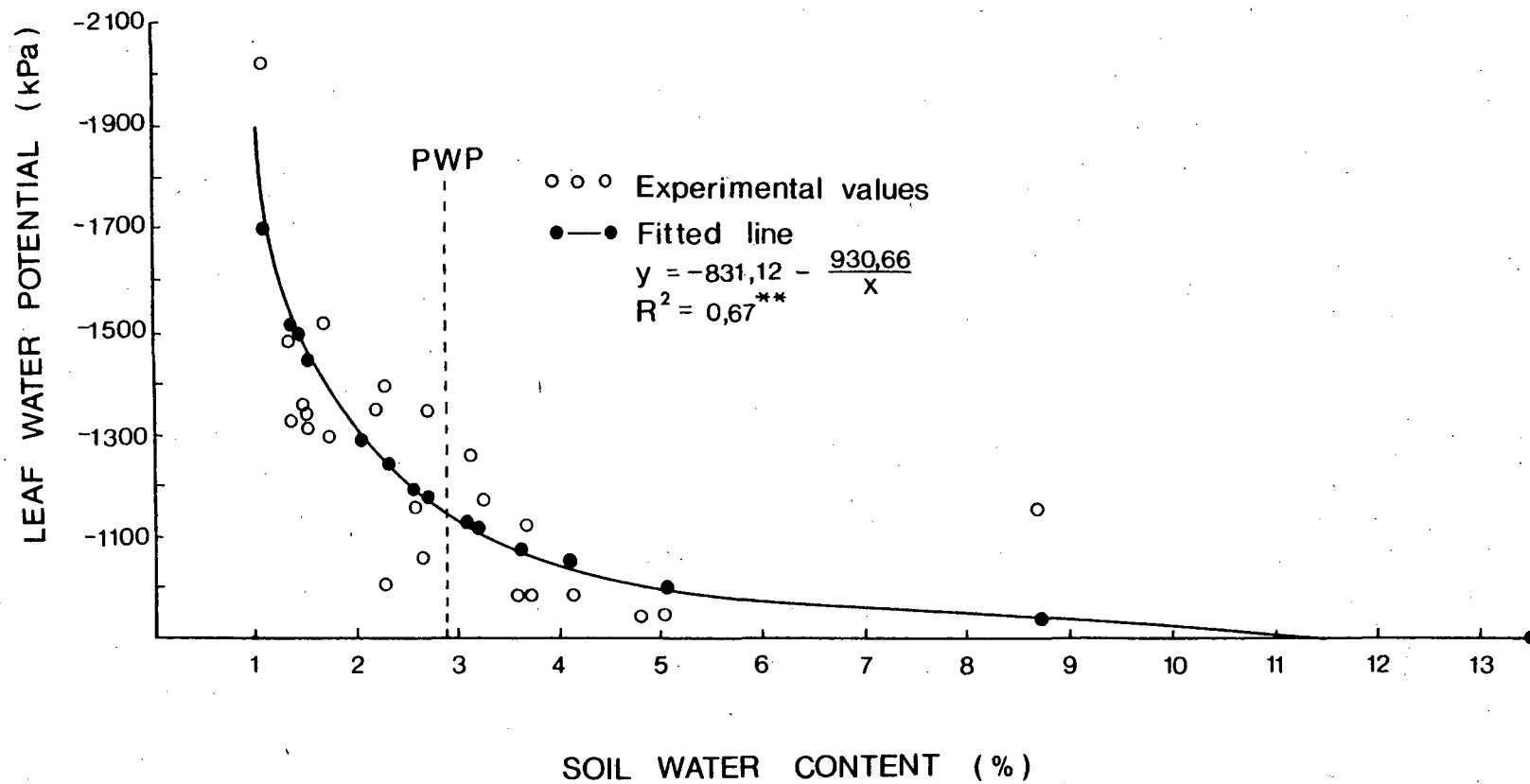
Fig. 4: Relationship between leaf water potential of Colombar/99R and the water content (mass %) of a sandy soil.
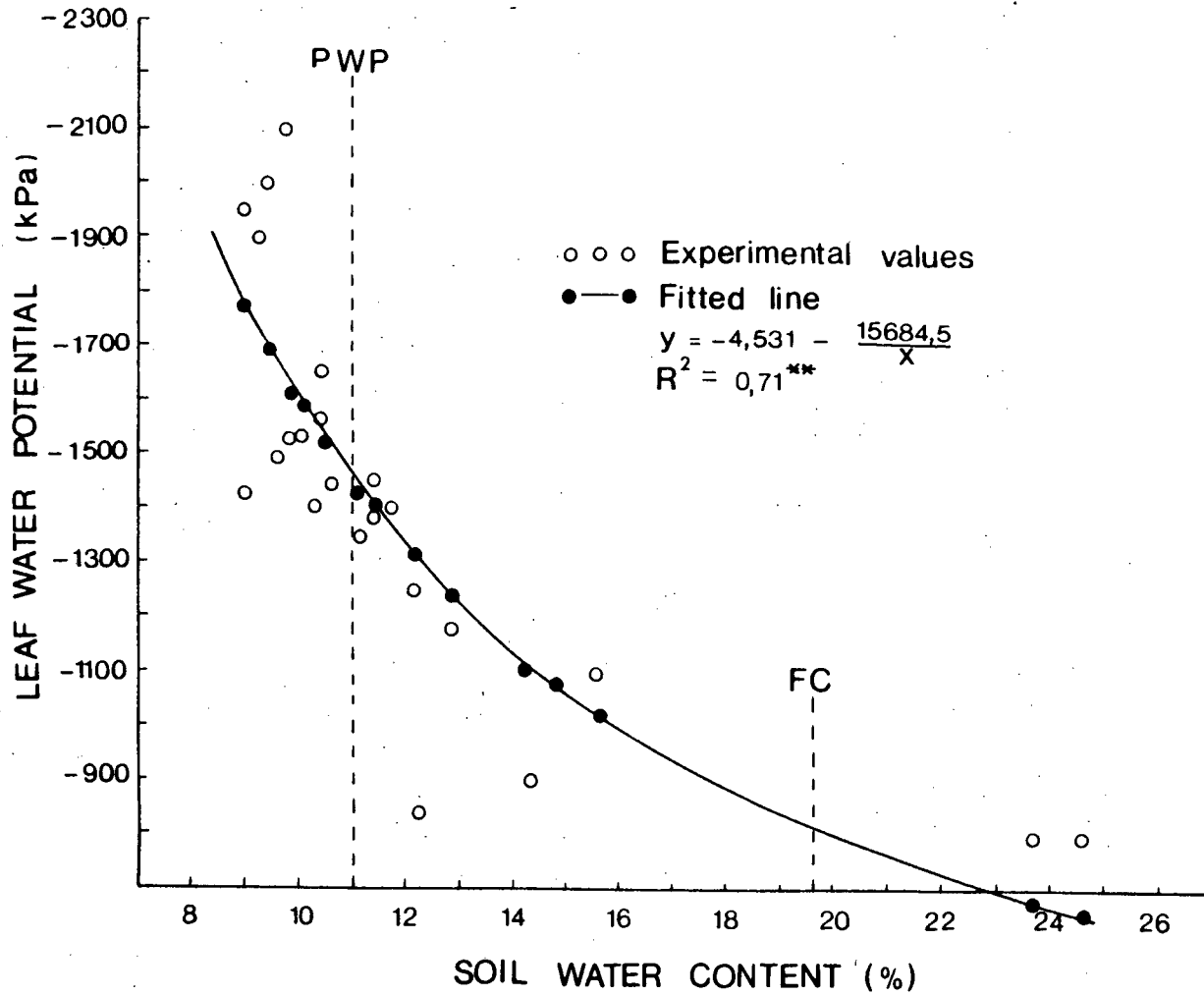
Fig. 5: Relationship between leaf water potential of Colombar/99R and the water content (mass %) of a sandy clay loam soil.
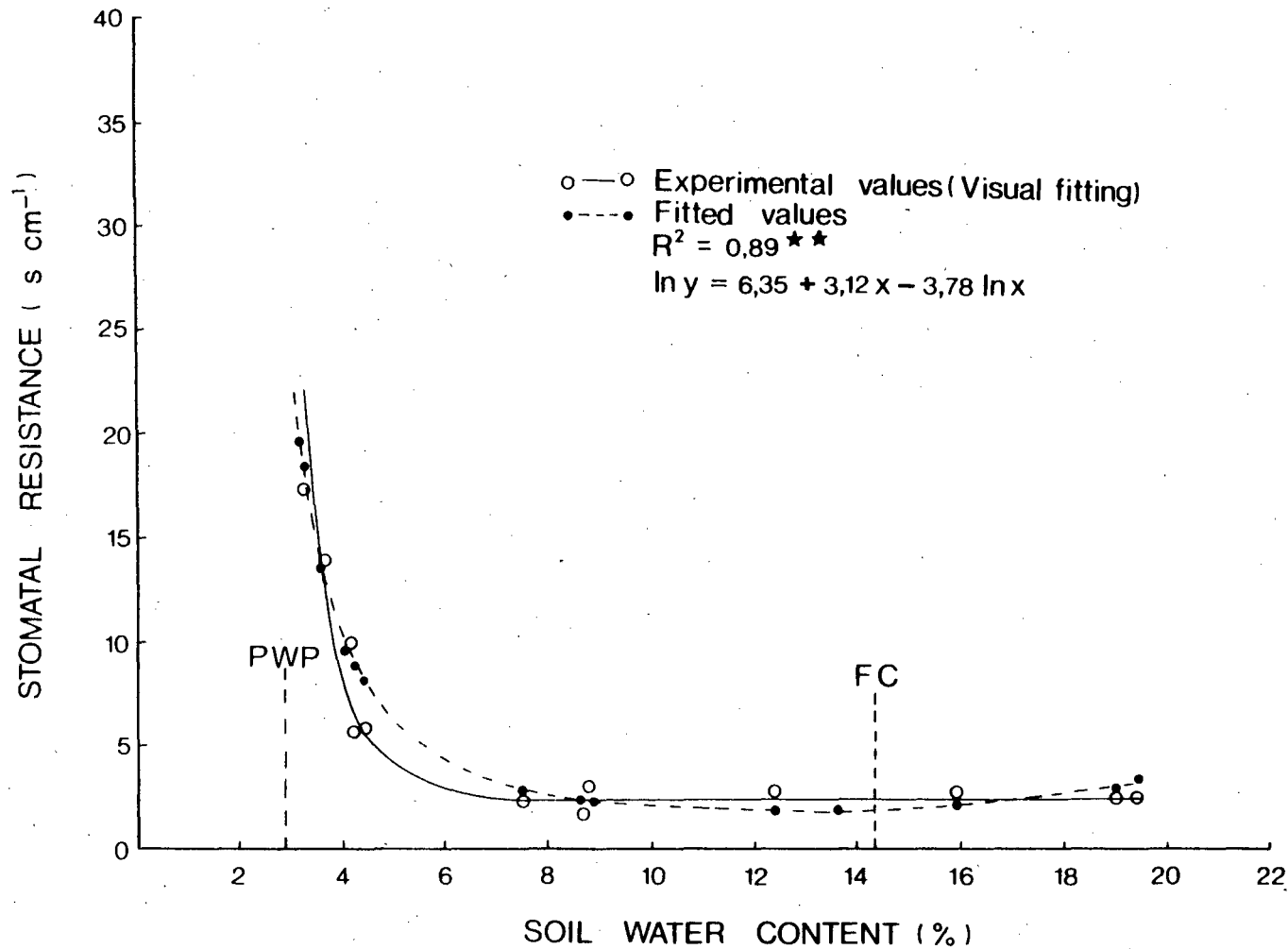
Fig. 6: Relationship between soil water content (mass %) of a sandy soil and stomatal resistance
of Colombar/99R in a pot experiment.
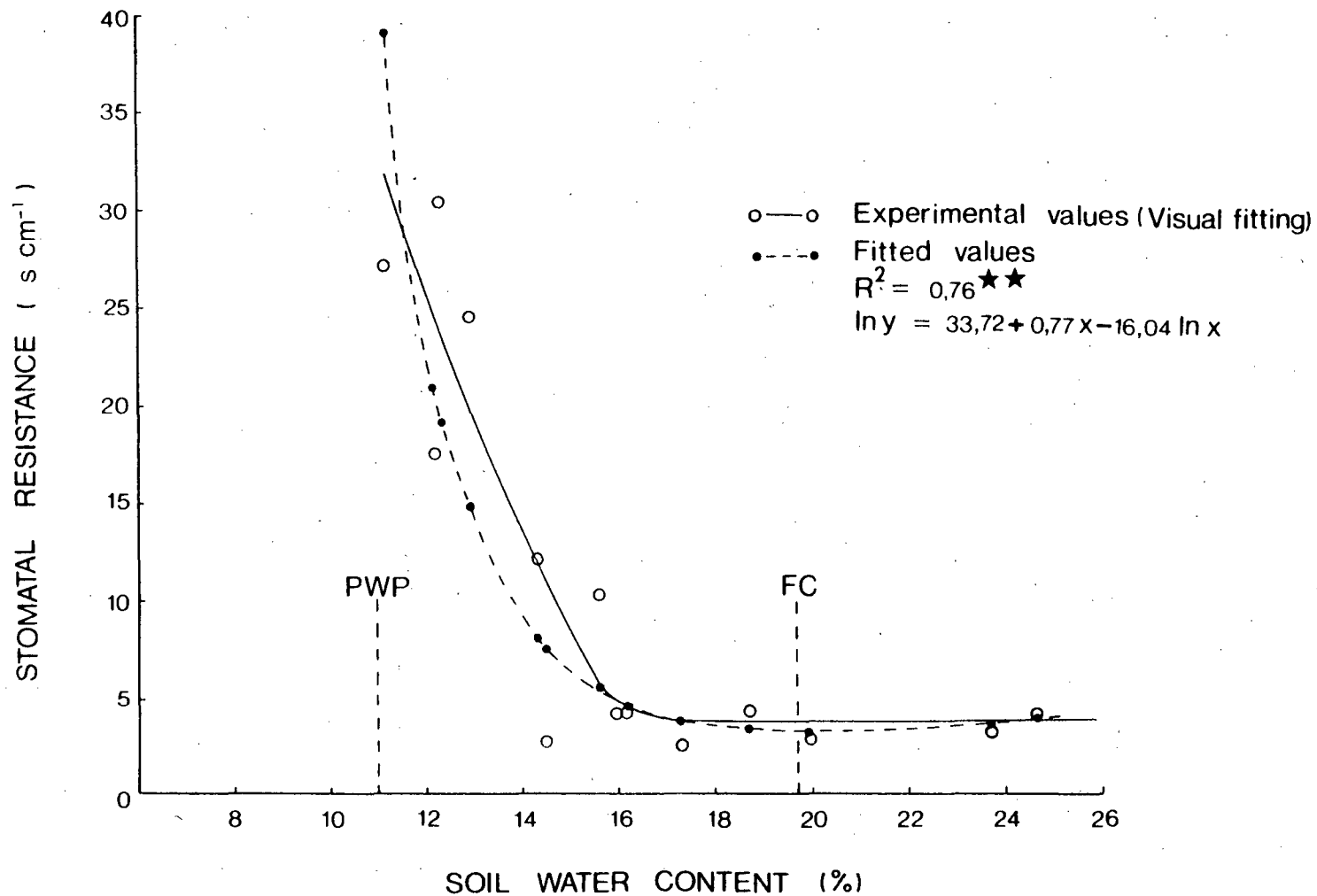
Fig. 7: Relationship between soil water content (mass %) of a sandy **loam** and
stomatal resistance of Colombar/99R in a pot experiment.
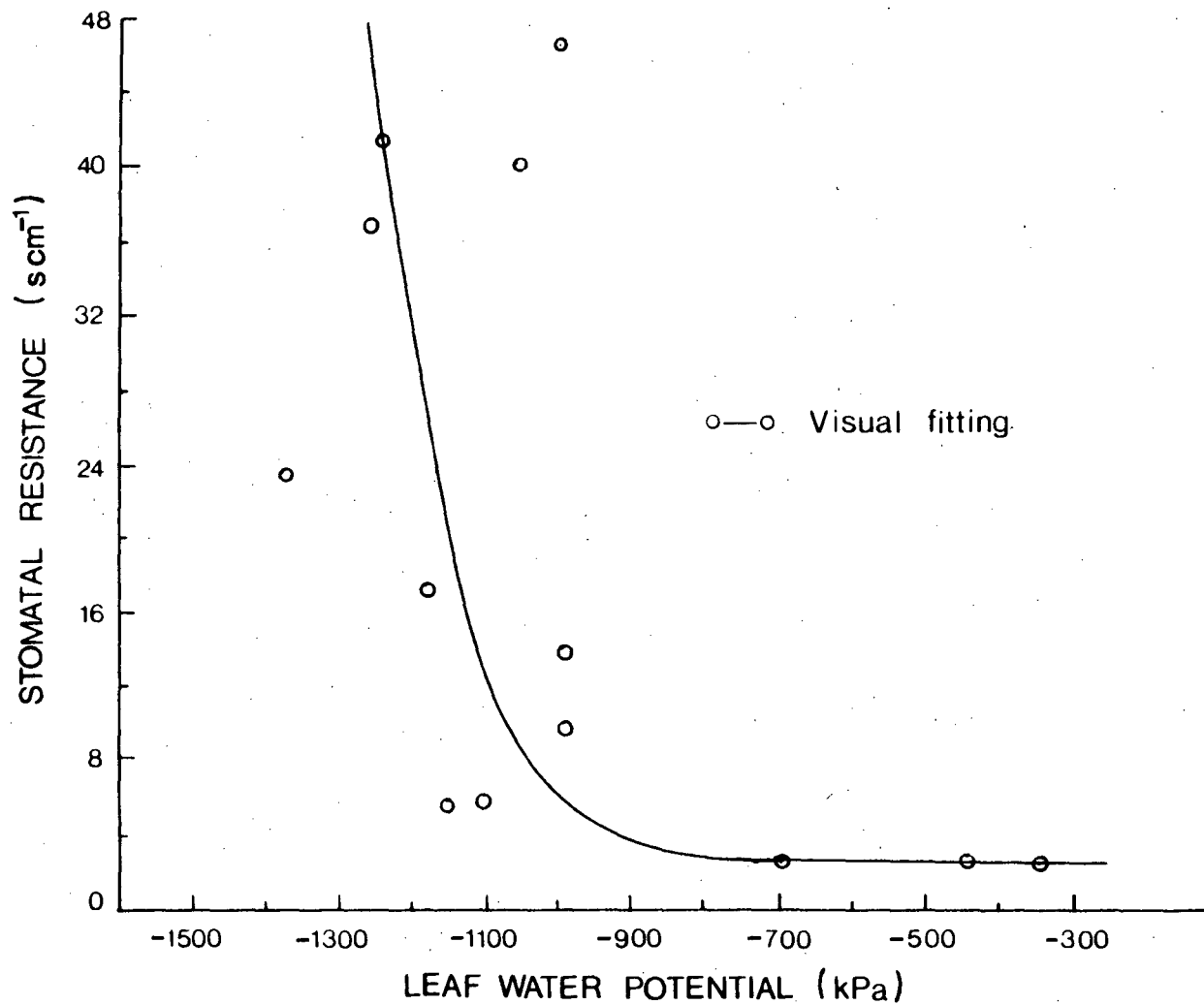
Fig. 8: A visual fitting to indicate the relationship between grapevine stomatal resistance and leaf water potential in a pot experiment with Colombar/99R on a sandy soil.
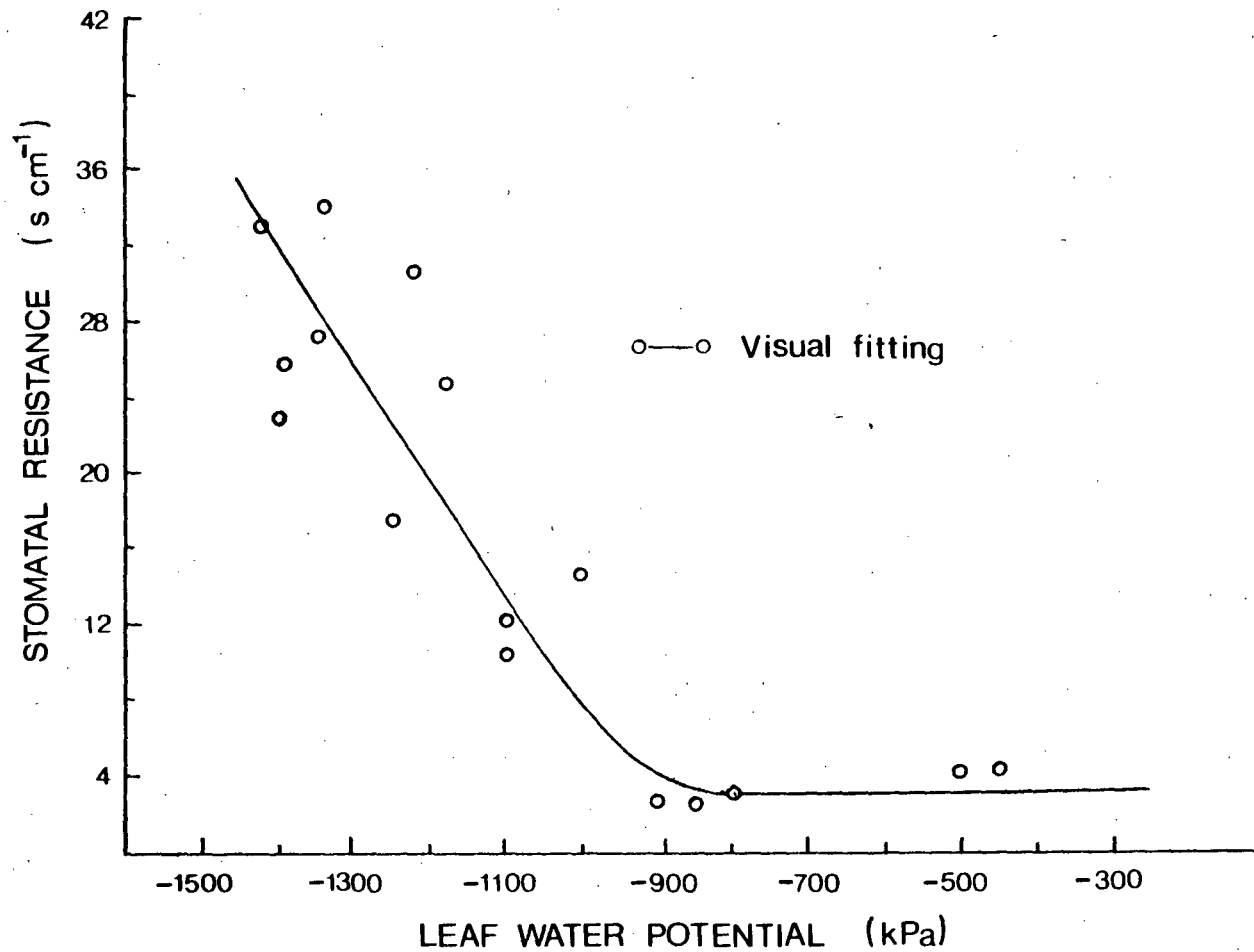
Fig. 9: A visual fitting to indicate the relationship between grapevine stomatal resistance and leaf water potential in a pot experiment with Colombar/99R on a sandy clay loam soil.

CHAPTER 3

RESPONSE OF GRAPEVINES IN POTS TO SOIL WATER REGIMES MAINTAINED BY AN
AUTOMATIC WATERING SYSTEM

INTRODUCTION

Three different approaches have been applied in studies regarding plant
response to water stress viz., water culture studies, pot experiments or
lysimeters, and field trials. Due to technical and managerial problems in
maintaining specific moisture regimes in soil (Slavik, 1974), studies in
water culture are most attractive. Solutions of polyethylene glycol (PEG),
a neutral polymer, were successfully used by several researchers to induce
water stress (Applegate, 1960; Lagerwerff, Ogata & Eagle, 1961; Lawlor,
1970; Frota & Tucker, 1978; Gergeley, Korcak & Faust, 1980; Van Zyl &
Kennedy, 1983). However, in a water culture, water stress is induced by os-
motic potential, as opposed to mainly matric potential in soil. Further-
more, with drying of soils the resistance to water flow between soil and
roots increased as a result of decreased soil root contact (Herkelrath, Mil-
ler & Gardner, 1977) and a decrease in unsaturated hydraulic conductivity
(Hanks & Ashcroft, 1980), both factors which do not play a role in a water
culture.

From a practical point of view the combination of field trials with pot ex-
periments seems to be an excellent way of studying water relations of agri-
cultural crops (Sommer & Bramm, 1978). Soil conditions can be more accura-
tely controlled in pots than in the field, but even in pots, it remains a
major problem how to subject plants to various known and controlled levels
of water stress. Various types of so-called auto-irrigators have been used
to achieve this goal. In 1918, Livingston (Kramer, 1983) supplied water

to pots through a porous ceramic cone attached to a water reservoir and buried in the pot. The same principle was used by Read, Fleck & Pelton (1962) who varied the matric potential by lowering the reservoir below the pot. The uniformity of water distribution was poor, however. Double walled pots with a porous inner wall and space for water between the walls, improved the water distribution but could still not supply the water requirement of large rapidly transpiring plants (Richards & Loomis, 1942). Researchers tried to overcome the problem of poor water distribution and low application rate by using more ceramic cells per pot (Hack, 1971; Sommer, 1981). In his pot experiment, Hack (1971) used ceramic cells with large flat sides. These cells were arranged radially around the plant in such a way that no point in the soil was more than 25mm from a water supplying surface. In other studies water was continuously supplied to potted plants by means of glass wool wicks and through cappilary rise from a sand box on which the pots were placed (Kramer, 1983). The occurrence of water potential gradients is a problem inherent to these techniques.

Attempts at controlling the soil water potential in pots at a specific level have been approached in different ways. Read et al. (1962) placed the auto-irrigated pots at different heights above the water supply. Moinat (1943) placed his pots on top of sand columns of different heights standing in water. Hack (1971) connected a water barostat reservoir to the auto-irrigator cells. The reduction of hydrostatic pressure below atmospheric could be controlled by adjusting the height of the reservoir relative to the centre of the auto-irrigator cells. Alvarez & De Datta (1977) controlled the soil water tension in their auto-irrigation system with the aid of Hg-traps, the functioning of which were controlled by the length of the Hg-column. A vacuum pump, electronic control equipment and storage waterbottles connected to ceramic cells in the pots were successfully used by Sommer (1981) to maintain different soil water potentials in studies with sugar beet.

In contrast to the abovementioned methods most investigators (Kramer, 1983) followed an approach resembling the natural process, i.e. wetting the soil to field capacity and letting it dry to a predetermined moisture level. This method requires frequent watering and determination of soil water status. Water applications following this approach can also be automated by a weighing system which controls a valve (Kramer, 1983). An air-lift system of automatic irrigation in pot experiments (Haahr, 1975) can supply water, but no control over the soil water status.

The object of this investigation was to (a) develop a simple and efficient method of maintaining soil water regimes in pots and (b) assess grapevine response to such regimes as part of a series of experiments which also included a study in a glasshouse as well as a field trial.

MATERIALS AND METHODS

Colombar/99R vines (clone 2/1154), visually selected for uniformity, were planted in 50dm^3 (height = 440 mm; diameter = 380 mm) earthenware pots. Each pot was filled with 51,3 kg (oven dry mass) of sandy soil (10,5% coarse sand (2,0 - 0,5 mm); 45,5% medium sand(0,5 - 0,2 mm); 37,4% fine sand (0,2 - 0,02 mm); 5,6% silt (0,02 - 0,002 mm); 0,0% clay (< 0,002 mm)), thoroughly mixed with manure at a ratio of 10 : 1 on a volume basis. A 50mm layer of gravel (fraction size = 10 - 15 mm diameter) on the bottom of each pot, served to drain possible excess water.

Different soil water regimes were maintained with the aid of an automatic watering system which became operative at a predetermined soil water potential and applied a specific quantity of water. In preliminary tests, attempts were unsuccessful to supply one year old vines with water through cylindrical ceramic cells (two per pot) of 300 mm length, 26 mm inner diameter,

8mm wall thichness and a pore diameter of 1,8 - 2,5m^{-6}.   Instead, these cells were used as soil tensiometers. In each pot one cell was installed in an upright position, 90 mm from the pot wall, to monitor the total soil depth from 20 mm below the soil surface down to 20 mm above the gravel layer (Fig. 1). The ceramic cells were sealed airtight by rubber stoppers and four cells were connected in series with the aid of strong nylon tubing (outer diameter = 3mm; inner diameter = 2mm) (Fig. 1). The first of the group of four cells was connected to an U-shaped mercury manometer: The fourth cell (D) was equipped with an inlet tube (5) which was closed when the soil water potential was measured. Prior to installation, all cells were saturated with water. The soil water potential was indicated by the difference in Hg-levels in the manometer (1). These composite tensiometers were completely filled with water. Air could be removed from the system by placing the inlet tube (5) of the last ceramic cell (D) in a beaker of water and applying suction to the manometer. As soon as all the mercury gathered in one leg of the manometer, air and water bubbled through, thus preventing mercury from being removed from the system. To facilitate this flow of air and water through the Hg, one leg of the manometer had a larger diameter (Fig. 2). Manometer readings could be calibrated in situ by leaving the inlet tube (5) of the last ceramic cell (D) open to the beaker of water for a few minutes after de-aeration.

The water supplying part of the system consisted of solenoid valves (13) connected by a 10mm polythene pipe to water reservoirs (6) (Fig. 1) each of which supplied water to the four pots of a different treatment. A polystyrene float (8) equipped with a thin metal rod was placed inside every water reservoir (6). An adjustable metal disk screwed onto the rod activated or de-activated two micro-switches (9,9) depending on the movement of the float. A small magnet (10) was mounted in such a way as to keep the upper micro-switch closed once it was switched off.

Two thin insulated wires with bare tips were placed in the manometer. One wire was left in contact with the Hg while the other one was pushed past the bend of the manometer until it reached a predetermined height. The second wire served as a switch which opened the solenoïd valve when the mercury column rose to the tip of the wire. A transformer supplied the necessary 24 V electrical current. In the electrical control system (12) a relay switch with 8 connecting points controlled the functioning of the solenoïd valve after the micro-switches were opened or closed (Fig. 3).

Functioning of the Automatic Watering System

A decrease in soil water potential caused the Hg in the manometer to rise and upon contact with the uninsulated tip of the electrical wire, the circuit was closed, the solenoïd valve opened and water flowed into the reservoir (6). The rising water level lifted the float and on a predetermined level the upper micro-switch and consequently also the solenoïd valve was switched off. At that stage water already started to flow through tubes (7) of the same length to pots receiving the same watering treatment. Siphoning of water from the container started shortly before the correct volume of water had flown into it and the outlets of watering pipes were not positioned too close to the filter candles to prevent premature wetting of the ceramic tensiometer causing the Hg to fall back and break the electrical contact.

The upper micro-switch remained closed due to the magnet and was proof to the researcher that water had been applied. The watering process could not start again before the float had reset the lower micro-switch. The upper micro-switch had to be reset by hand. Removal of the magnet, ensured that the watering precess could continue automatically at a specific soil water potential.

The quantity of water to be applied per irrigation was calculated from soil water retension curves (Fig. 4), determined on undisturbed soil cores. Field water capacity was determined in the pots after the potted soil had been watered thoroughly, and covered to prevent evaporation until regular tensiometer readings and gravimetric soil sampling indicated that water redistribution was minimal.

The functioning of the ceramic cells was assessed during January and February 1981 with the help of 12 tensiometers which were installed at three depths (50mm, 180mm and 300mm) 30mm from the ceramic cells in all four replication pots of one treatment. Correlation coefficients were determined for the relationship between the soil water potential readings of the ceramic cells and the average reading of all 12 tensiometers. Readings of those two tensiometers which gave the maximum and minimum values respectively at a particular time, were also correlated with the ceramic cell readings. The experiment was conducted in open air at Stellenbosch on ground covered by short grass. Consequently the micro-climate did not simulate a vineyard environment. The pots were protected against rain by rain shields cut from flexible polystyrene material and fitted closely around the stems of vines and over the pot itself (Fig. 5). These caps could be opened or closed with the aid of adhesive strips. The pots were covered from bud burst to véraison, but uncovered during the ripening phase of the grapes when the possibility of the occurrence of rain was minimal.

Experimental Layout and Procedure

Vine response to soil water potential was studied during three growth stages, viz.,

Phase I   = Bud burst   - flowering

Phase II   = Flowering   - véraison

Phase III = Véraison   - harvest

The pot experiment consisted of 12 treatment combinations (Table 1). During the first two phenological stages vines were grown at soil water potentials of either -5 kPa or -20 kPa. A third water regime of -80 kPa was added during the important ripening stage. Data for individual treatments were compiled and standard two-way and three-way analyses of variance applied to the data sets.

A treatment consisted of four replicate vines. During the first season all pots were maintained at the same moisture regime (-20 kPa) to establish the vines. At the end of the first season trunk circumference and pruning mass were determined as covariates for plant response to treatments during the second season.

During the trial season all vines were summer pruned to an average of five shoots per plant and shoot lengths were measured weekly. Fruit set was determined by covering one inflorescence per vine in a thin gauze bag before flowering. The gauze allowed air circulation, but retained all flowers and berries which dropped. Counts were made of berries which reached maturity and of those which dropped. Fruit set was then calculated as follows :

$$\text{Fruit Set (\%)} \quad = \quad \frac{M}{M + B + F} \quad \text{x } 100$$

where,

      M = mature berries (number)

      B = berries which dropped (number)

      F = flowers which dropped (number)

Berries were sampled twice during the season, namely at véraison and again during harvesting. These berries were dejuiced and the total titratable acidity (TTA), sugar concentration and pH of the sap determined (see Chapter 4 for details of techniques). Berry fresh mass was used as a parameter of

yield response to soil water potential. During winter the ensuing shoot growth was finally assessed in terms of shoot length and shoot mass.

Trunk growth was determined on a seasonal basis by measuring trunk circumferences at pruning time. Fluctuations in trunk diameter were followed with the aid of dial gauges screwed into the wood and which were read daily at 06h00 and 14h00. Preliminary tests proved that these two times represented maximum and minimum values respectively, during the diurnal fluctuation of trunk diameter. Trunk growth was determined by calculating the change in trunk diameter between successive days.

On several days during the ripening stage of the grapes (January) stomatal resistance (Rs) and leaf water potential (LWP) were determined on four vines of the three soil water regimes each (see chapter 6 for detailed description of apparatus and techniques).

RESULTS AND DISCUSSION

The different soil water regimes were very successfully controlled with the aid of the automatic watering system. It could function for long periods with a minimum of attention and could supply the required quantity of water (2 - 3 dm^3/plant/day during the period of peak consumption) at precisely the correct soil water potential. In addition to its role as an electrical switch, the manometer also indicated soil water potential. The variation in soil water potential as a result of consumptive water use and irrigation alternatively, is illustrated for two treatments in Figs. 6 & 7.

The irrigation frequency was considerably higher (28%) at a soil water potential of -20 kPa in comparison with -80 kPa. Soil water potentials decreased very rapidly below -10 kPa (in correspondence with the soil water

retension curve) which would have made it almost impossible to control the water regimes manually.

The Hg-manometers used in the experiment can also serve as control valves if water is to be applied to pots through ceramic cells. In this respect the Hg-manometer is extremely effective and much simpler and cheaper than devices used by other researchers (Hack, 1971; Alvarez & De Datta, 1978; Sommer, 1981).

Problems were initially experienced with corrosion of the copper contact wire inside the manometer. This problem was, however, solved by soldering a Platinum tip on to the copper.

Uncertainty existed as to the exact soil water potential measured by the ceramic cells since a potential gradient existed over its entire length. Average readings of 12 tensiometers (3 depths x 4 pots) installed as controls, corresponded well (r = 0,91) with those of the ceramic cells (Fig. 8). The slightly lower average tensiometer readings compared to the ceramic cell-/manometer system could be ascribed to better root distribution around the cells which at that stage had been installed for almost 6 months, in contrast to the tensiometers which were installed shortly before the comparative investigation. Maximum tensiometer readings did not correlate well (r= 0,68) with those of the ceramic cell/manometer system. Despite a high correlation coëfficient (r = 0,93), minimum tensiometer readings deviated much from the ceramic cell/manometer system below soil water potentials of approximately -15 kPa (Fig. 8). The latter deviation would probably have increased further if more time were allowed for normal root growth around the tensiometer cups.

Soil water was not depleted uniformly in the pots. Tensiometer readings showed that the upper 100 mm layer of soil dried initially, after irrigations, rapidly to a value of approximately -10 kPa. From then onwards tensiometers at the second depth (180 mm) indicated a faster depletion rate in

the middle part of the pots, probably due to a higher root concentration at that depth.

Consumptive Water Use

The quantities of water required to replenish the soil reservoir at the different soil water regimes to field water capacity were as follows:

$$- 5 \text{ kPa} = 2,65 \text{ dm}^3/\text{pot}$$
$$-20 \text{ kPa} = 6,16 \text{ dm}^3/\text{pot}$$
$$-80 \text{ kPa} = 6,99 \text{ dm}^3/\text{pot}$$

During phase I and phase II, while the pots were covered, 46,0% more water was transpired by grapevines maintained at a -5 kPa soil water regime than by those at -20 kPa (Table 2). This can most probably be ascribed to a bigger leaf area of the wetter soil water regime. During phase III the consumptive water use at the three soil water regimes was comparable.

Plant Response

Shoot mass and shoot length as parameters of vegetative growth increased significantly at a -5 kPa soil water regime compared to -20 kPa during phase II and III (Table 3). No effect was evident during phase I. Shoot elongation rates at a soil water potential of -5 kPa were significantly higher than those of a -20 kPa regime (Fig. 9). This result once again underlined the sensitivity of shoot elongation as an indicator of water stress. The generally high rate of shoot elongation during the first 60 days after bud burst was a result of the natural growth pattern of grapevines. After flowering, shoot elongation rates decreased rapidly. Shoots continued to elongate slowly until shoot length measurements were terminated in December

due to to mechanical damage to the growing tips.

Trunk growth as measured by dial gauges, occurred in phase I and II, but stopped at véraison irrespective of treatment (Fig. 10). The same trunk growth pattern was found in the field experiment, but in the latter case trunks even became thinner. A comparison of trunk circumferences at the end of the season showed no response to soil water potential during phase I, but the -5 kPa treatment resulted in thicker trunks during phase II (Table 3).

Fruit set was not affected by the two soil water regimes (Table 4). This finding is in agreement with results obtained in the field experiment and fruit set values were of the same order in both trials. It has been demonstrated with other cultivars that severe stress can be detrimental to fruit set (Alexander, 1964; Hofäcker, 1976).

The two soil water regimes (-5 kPa and -20 kPa) did not differ significantly at véraison with regard to sugar, TTA and pH. Berries were, however, significantly larger at -5 kPa during phase II (Table 4).

Must analyses during harvesting (Table 5) showed no response of TTA or pH to the three soil water regimes, but sugar concentration decreased in the order -5 kPa > -20 kPa > -80kPa. This deviation from findings in the field was most probably due to the absence of an effective canopy which normally would have induced different micro-climates as well as to the very low grape yields obtained in pots compared to a vineyard. In the vineyard situation the product (sugars) of increased photosynthesis as a result of low water stress, is normally 'diluted' by a higher grape yield with a lower sugar concentration as a consequence.

Diurnal changes in LWP at the three soil water treatments showed the typical pattern viz., high at night with a minimum during the hottest part of the day (Fig. 11). LWP decreased rapidly at all three soil water regimes between 05h00 and 10h00 on this particular day. The 10 kPa difference in soil water potential between the -5 kPa and -20 kPa treatments was not clearly reflected in the LWP at that stage. This difference in LWP would have been much more pronounced between 10h00 and 12h00, before the -20 kPa treatment was irrigated as had been found on other dates (Table 6). After the irrigation the LWP as well as the soil water potential of the two treatments were the same (Fig. 11). However, the soil water potential of the -80 kPa treatment decreased gradually during the day. At 05h00 on 23/1/81 the LWP difference between the two wet treatments (-5 and -20 kPa) and the dry soil water regime (-80 kPa) was still 60 kPa while the corresponding difference in soil water potential was 46 kPa. Stomatal resistance showed no consistent response pattern to the different soil water regimes and consequently this relationship was further investigated in the field (see Chapter 6).

CONCLUSION

Due to the rapid decrease of the soil water potential in pots, it is impractical to conduct water regime experiments in small containers without an automatic watering system. Such a system was developed and employed successfully in a study on the water relations of grapevines. The auto-irrigation system came into operation at exactly the correct soil water potential monitored by ceramic cells. Mercury manometers activated solenoïd valves which were shut off automatically after the correct volume of water had been applied to each pot. Consequently the system functioned by itself. In contrast to tensiometers, the large ceramic cells used in the experiment monitored soil water potential over the entire soil depth. There are good grounds for believing that these readings reflected the average soil water potential at different depths and in all pots of one treatment.

The grapevines responded differently to the soil water regime treatments during different phenological stages. Pruning mass, cane length and trunk circumference were not affected by the two soil water regimes of -5 kPa and -20 kPa during phase I (bud burst - flowering). However, during phase II (flowering - véraison) and phase III (véraison - harvest) all three these parameters of vegetative growth had highest values at -5 kPa. Trunks displayed a high growth rate during phase II, but growth stopped at véraison, supporting data obtained in a vineyard.

Berry mass was deleteriously affected by a decrease in soil water potential from -5 kPa to -20 kPa during phase II, but not in phase I. This finding, again confirmed field results and emphasized the sensitivity of berry growth to water stress during phase II. Fruit set was not affected by the two soil water potentials tested.

The three parameters of grape quality viz., sugar concentration, TTA and pH were not affected by the water regime treatments at véraison. In contrast to results of field experiments, the sugar concentration decreased with decreasing soil water potential. Furthermore, the lack of response with regard to TTA was also contrary to the increase of TTA found with increasing irrigation frequencies in a vineyard. The absence of an effective microclimate induced by the vine canopy as well as the low yields obtained in the pots, were most probably a contributing factor in the result. Results of pot experiments should therefore be interpreted carefully. Ideally these results should be assessed in conjunction with field experimentation.

Measurements of leaf water potential clearly showed that the soil water regimes imposed different levels of water stress in the plant. In this study stomatal resistances were less sensitive to soil water regime than LWP.

LITERATURE CITED

ALEXANDER, D. Mc E., 1964.   The effect of high temperature regimes on short periods of water stress on development of small fruity Sultana vines. Aust. J. Agric. Res. 16, 817-823.

ALVAREZ, E.I. & DE DATTA, S.K., 1977.   Automatic feedback control to maintain constant soil moisture tension in the study of drought tolerance in rice.   Soil. Sci. Soc. Am. J.   41, 452-454.

APPLEGATE, H.G., 1960.   Freezing point depressions of Hoagland's "Carbowax" systems. Nature 186, 232-233.

FROTA, J.N.E. & TUCKER, T.C., 1978.   Salt and water stress influences nitrogen metabolism in Red Kidney beans. Soil. Sci. Soc. Am. J. 42, 743-746.

GERGELEY, I., KORCAK, R.F. & FAUST, M., 1980.   Polythylene glycol induced water stress effects on apple seedlings.   I Methodology, water consumption and dry matter production. J. Amer. Soc. Hort. Sci. 105, 854-857.

HAAHR, V., 1975.   Comparison of manual and automatic irrigation of pot experiments. Plant and Soil 43, 497-502.

HACK, H.R.B., 1971.   An improved method of soil moisture control with observation of tomato growth and water uptake. J. Exp. Bot. 22, 323-336.

HANKS, R.J. & ASHCROFT, G.L., 1980. Applied soil physics. Advanced Series in Agricultural Sciences 8, Springer Verslag, New York.

HERKELRATH, W.N., MILLER, E.E. & GARDNER, W.R., 1977. Water uptake by plants : I. Divided root experiments. Soil. Sci. Soc. Am. J. 41, 1033-1038.

HOFäCKER, W., 1976. Untersuchungen über den Einfluss wechselnder Bodenfeuchte auf Fruchtbarkeit, Beerenwachstum, Ertrag und Mostgewicht bei Reben. Die Wein-Wissenschaft 31, 1-8.

KRAMER, P.J., 1983. Water relations of plants. Academic Press, New York, London.

LAGERWERFF, J.C., OGATA, G. & EAGLE, H.E., 1961. Control of osmotic pressure of culture solutions with polyethylene glycol. Science 133, 1486-1487.

LAWLOR, D.W., 1970. Absorption of polyethylene glycols by plants and their effects on plant growth. New Phytol. 69, 501-513.

MOINAT, A.D., 1943. An auto-irrigator for growing plants in the laboratory. Plant Physiol. 18, 280-287.

READ, D.W.L., FLECK, S.V. & PELTON, W.L., 1962. Self-irrigating greenhouse pots. Agron. J. 54, 467-470.

RICHARDS, L.A. & LOOMIS, W.E., 1942. Limitations of auto-irrigators for controlling soil moisture under growing plants. Plant

Physiol. 17, 223 - 235.

SLAVIK, B., 1974. Methods for studying plant water relations. Ecological studies 9, Springer-Verslag, Berlin and New York.

SOMMER, C., 1981. A method for investigating the influence of soil water potential on water consumption, development and yield of plants. Soil & Tillage Research 1, 163-172.

SOMMER, C. & BRAMM, A., 1978. Wasserverbrauch und Pflanzenwachstum bei Zuckerrüben in Abhängigkeit von der Wasserversorgung. Landbauforsch. Völkenrode, 28, 151-158.

VAN ZYL, J.L. & KENNEDY, C.S., 1983. Vine response to water stress induced by polyethylene glycol. S. Afr. J. Enol. Vitic. 4, 1-5.

TABLE 1. Soil water potentials (kPa) maintained in a pot experiment with Colombar/99R grapevines

Treatment No.	Phenological Stage		
	I	II	III
1	−5	−5	−5
2	−5	−5	−20
3	−5	−5	−80
4	−5	−20	−5
5	−5	−20	−20
6	−5	−20	−80
7	−20	−5	−5
8	−20	−5	−20
9	−20	−5	−80
10	−20	−20	−5
11	−20	−20	−20
12	−20	−20	−80

I   = Bud Burst   − Flowering

II = Flowering   − Véraison

III = Véraison   − Harvest

TABLE 2. Consumptive water use of potted vines at certain physiological stages and at three soil moisture regimes

Soil Water Regime (kPa)	Irrigation (dm³/plant/day)		
	I*	II*	III
−5	0,76	1,43	2,44
−20	0,52	0,98	2,17
−80	−	−	2,25

I   =   Bud Burst   −   Flowering

II   =   Flowering   −   Véraison

III =   Véraison   −   Harvest

*   =   Pots covered

TABLE 3: Effect of two soil water regimes on vegetative growth during the various growth stages of grapevines

Soil Water Potential (kPa)	Pruning Mass (g vine^{-1})			Total Cane Length (m vine^{-1})			Trunk Circumference (mm vine^{-1})		
	I	II	III	I	II	III	I	II	III
- 5	320,55	363,77	350,26	5,378	5,920	5,831	64,3	66,2	66,4
- 20	314,82	271,61	285,11	5,559	5,016	5,105	63,9	52,1	61,8
D-Value(P$\leq$0,05)	NS	25,02*	25,02*	NS	0,630*	0,630*	NS	32*	32*

I	–	Bud Burst – Flowering
II	–	Flowering – Véraison
III	–	Véraison – Harvesting
*	–	Significant
NS	–	Not Significant

TABLE 4. Effect of soil water regime during two growth stages on berry development and composition at véraison

Water Regime (kPa)	Berry Set (%)		Sugar (°B)		Total Titratable Acidity (g dm^{-3})		pH		Berry mass (g/100 berries)	
	I	II	I	II	I	II	I	II	I	II
-5	35,80	35,40	7,27	7,59	32,67	32,27	3,38	3,40	83,53	100,85
-20	34,71	35,09	7,55	7,23	30,82	31,22	3,37	3,35	94,53	77,20
D-Value (P ≤ 0,05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	17,20[*]

I = Bud Burst – Flowering

II = Flowering – Véraison

* = Significant

NS = Not Significant

TABLE 5. Effect of soil water regimes on grape composition at harvest

Water Regime (kPa)	Sugar (°B)	Total Titratable Acidity (g dm⁻³)	pH
−5	18,85	8,50	3,14
−20	17,66	8,85	3,16
−80	16,99	8,81	3,16
D−Value (P ⩽ 0,05)	0,95*	NS	NS

* = Significant

NS = Not Significant

TABLE 6. Effect of soil water potential on leaf water potential of Colombar

vines at noontime (30/01/81)

Soil Water Potential (kPa)	Leaf Water Potential (kPa)
− 4,1	− 708
−18,7	−1199
−65,8	−1423

① Hg – Manometer
② Ceramic cell
③ Earthenware pot
④ Nylon tube
⑤ Rubber inlet
⑥ Water reservoir
⑦ Siphon
⑧ Float
⑨ Micro-switch
⑩ Magnet
⑪ Metal disc
⑫ Electrical control system
⑬ Solenoid valve
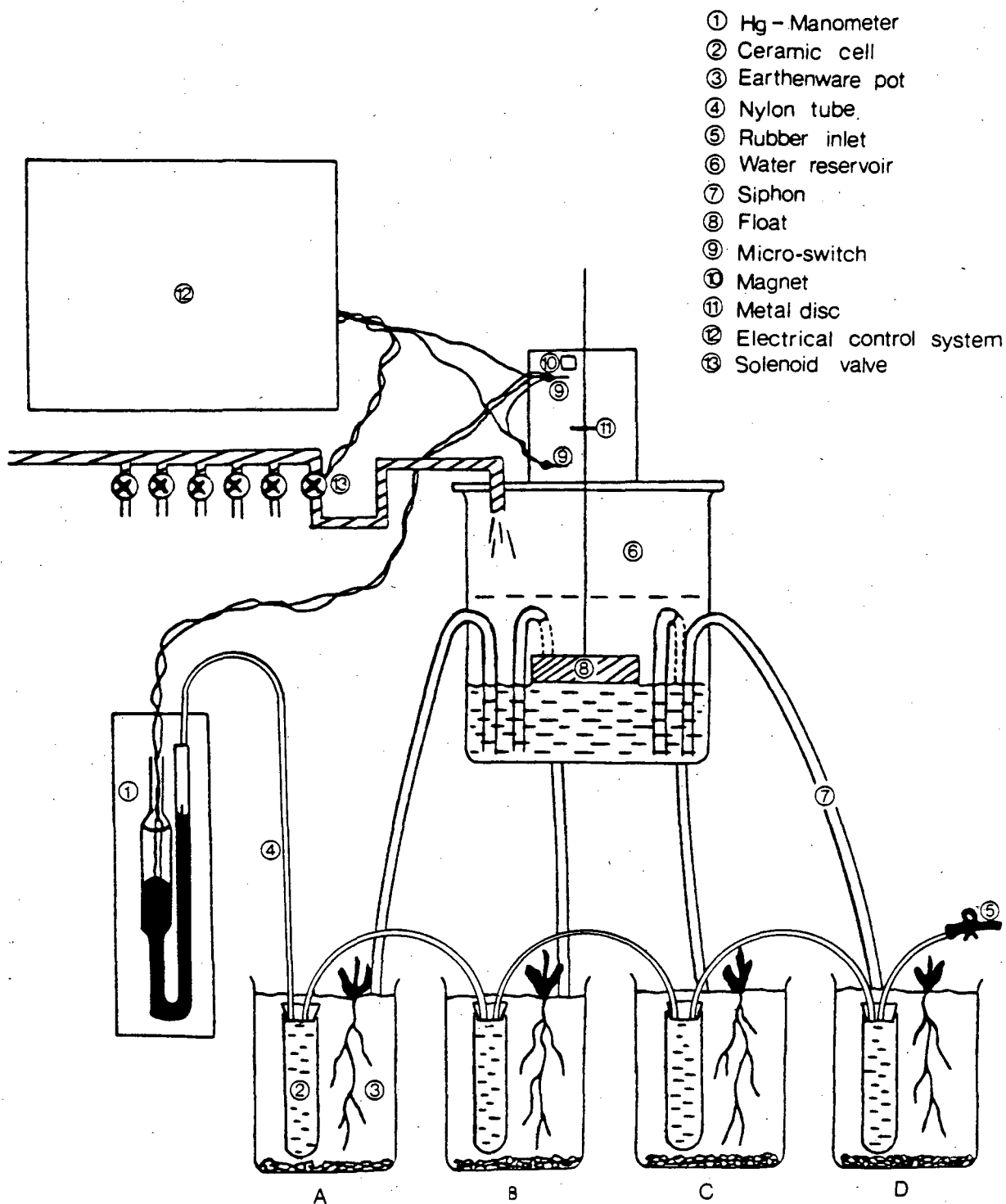
Fig. 1: Schematic illustration of auto-irrigation in a pot experiment with grapevines (not drawn to scale).
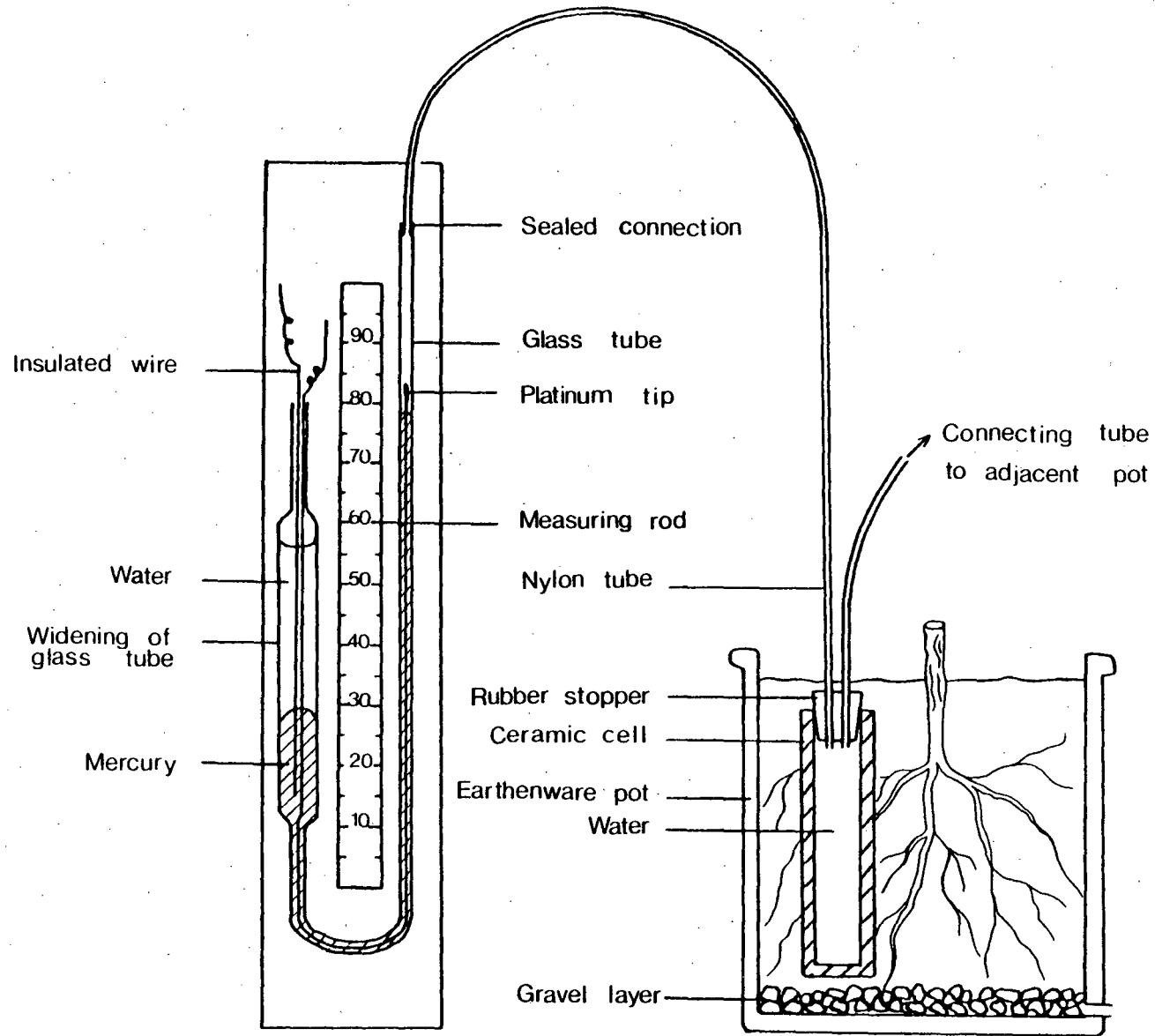
Fig. 2: Manometer and ceramic cell which measured and controlled the soil water potential (not drawn to scale).

M1 — Micro-switch
M2 — Micro-switch
NC — Normally closed
N.O. — Normally open
T — Transformer
S — Solenoid valve
R — Relay,8 pin,24V coil
R1 — Positive
R2 — Coil
R3 — Normally open
R4 — Normally closed
R5 — Normally closed
R6 — Normally open
R7 — Coil
R8 — Positive
AC — Alternating current
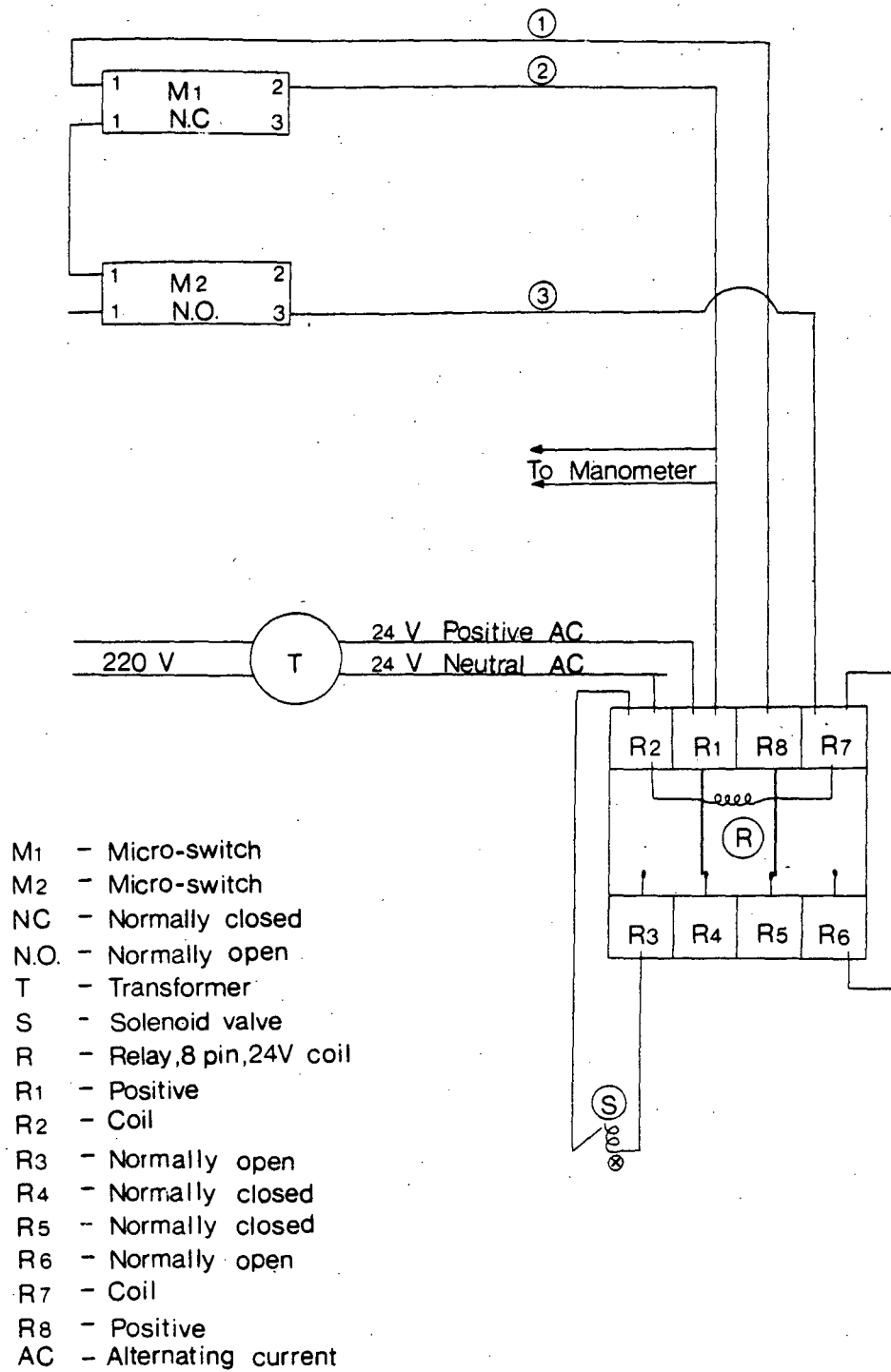
Fig. 3: Wiring diagram of the water supplying system used in
a pot experiment with grapevines.
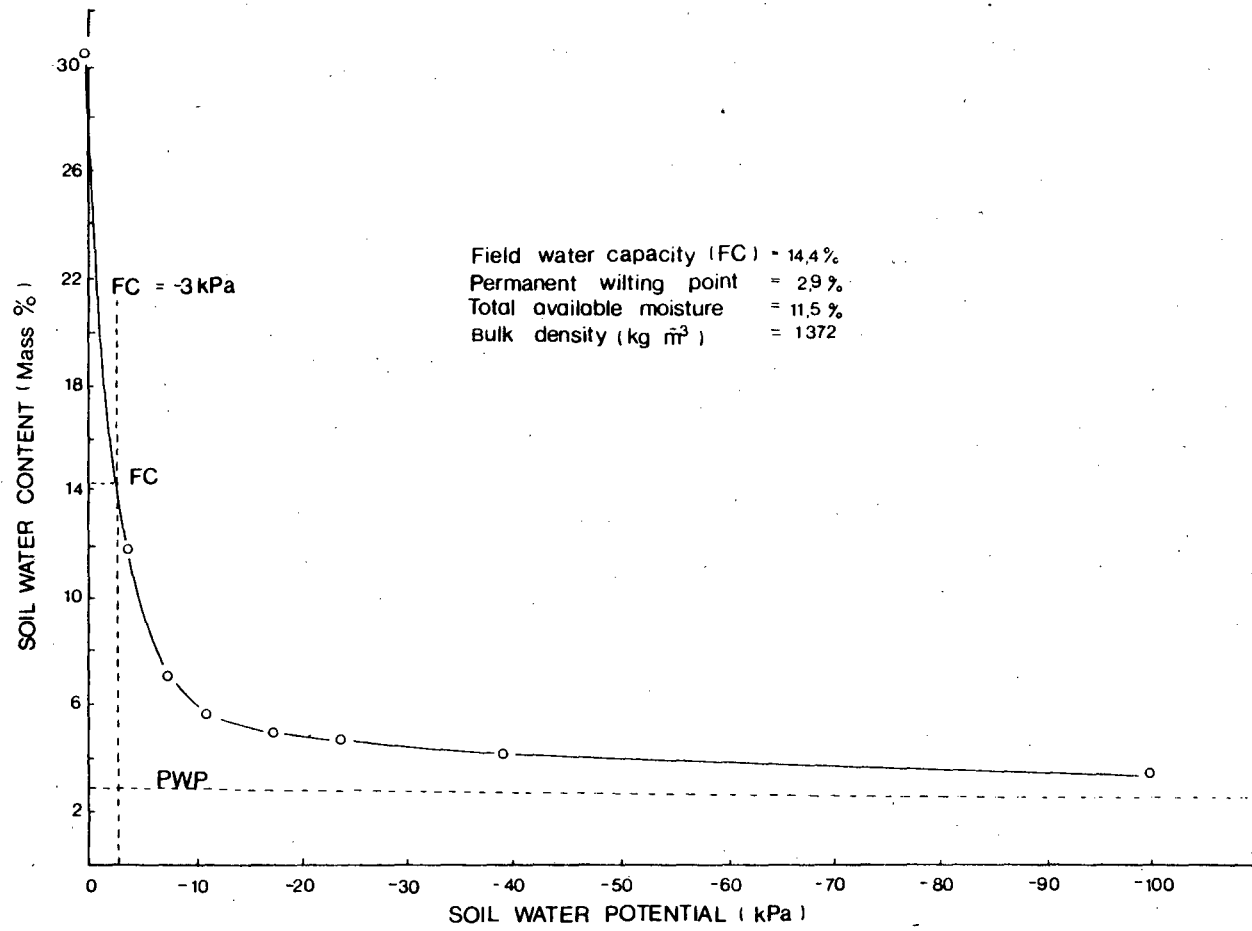
Fig. 4: Soil water retention curve for the potted soil.
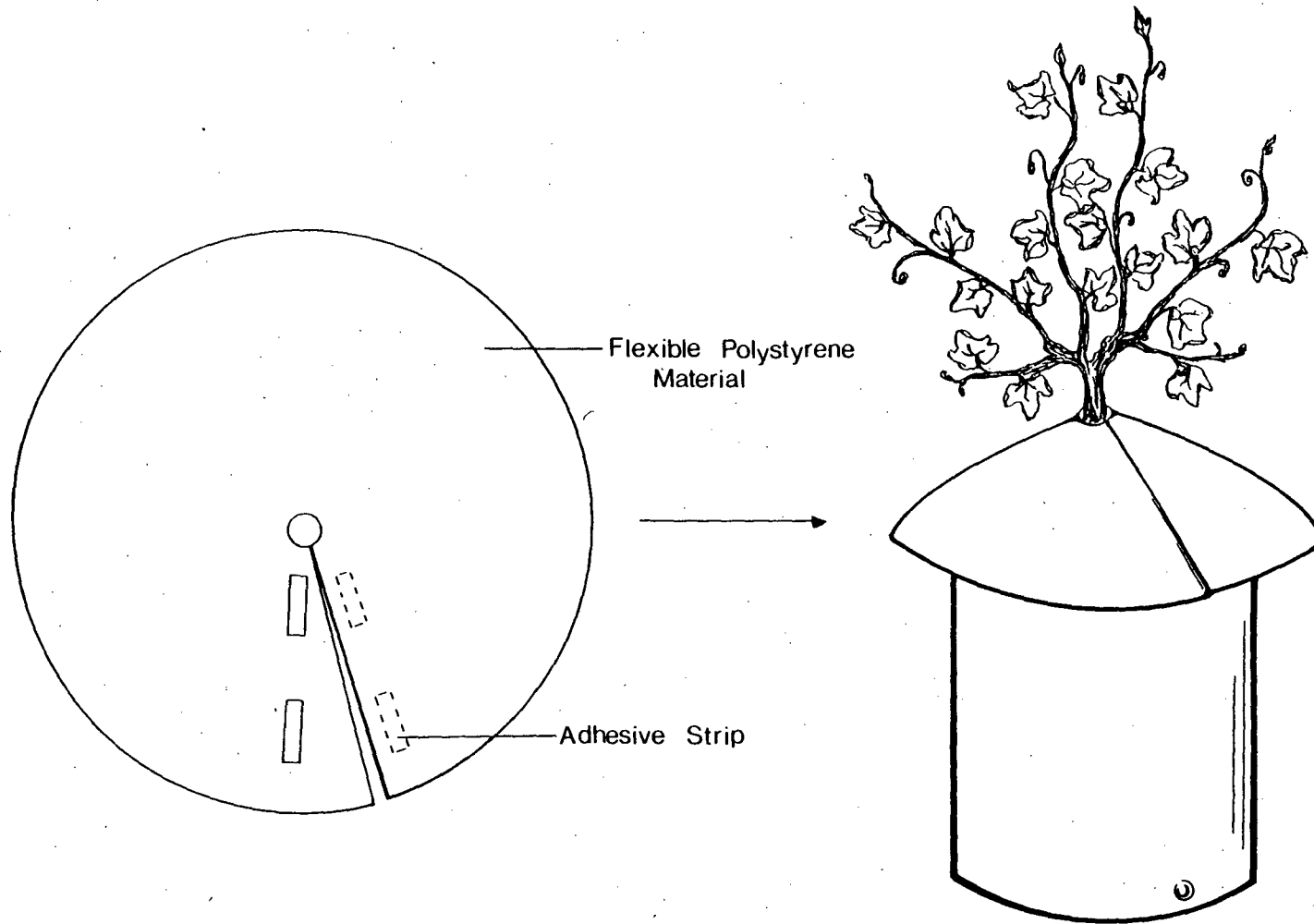
Fig. 5: Rooflet from polystyrene material used to shield the soil against rain.
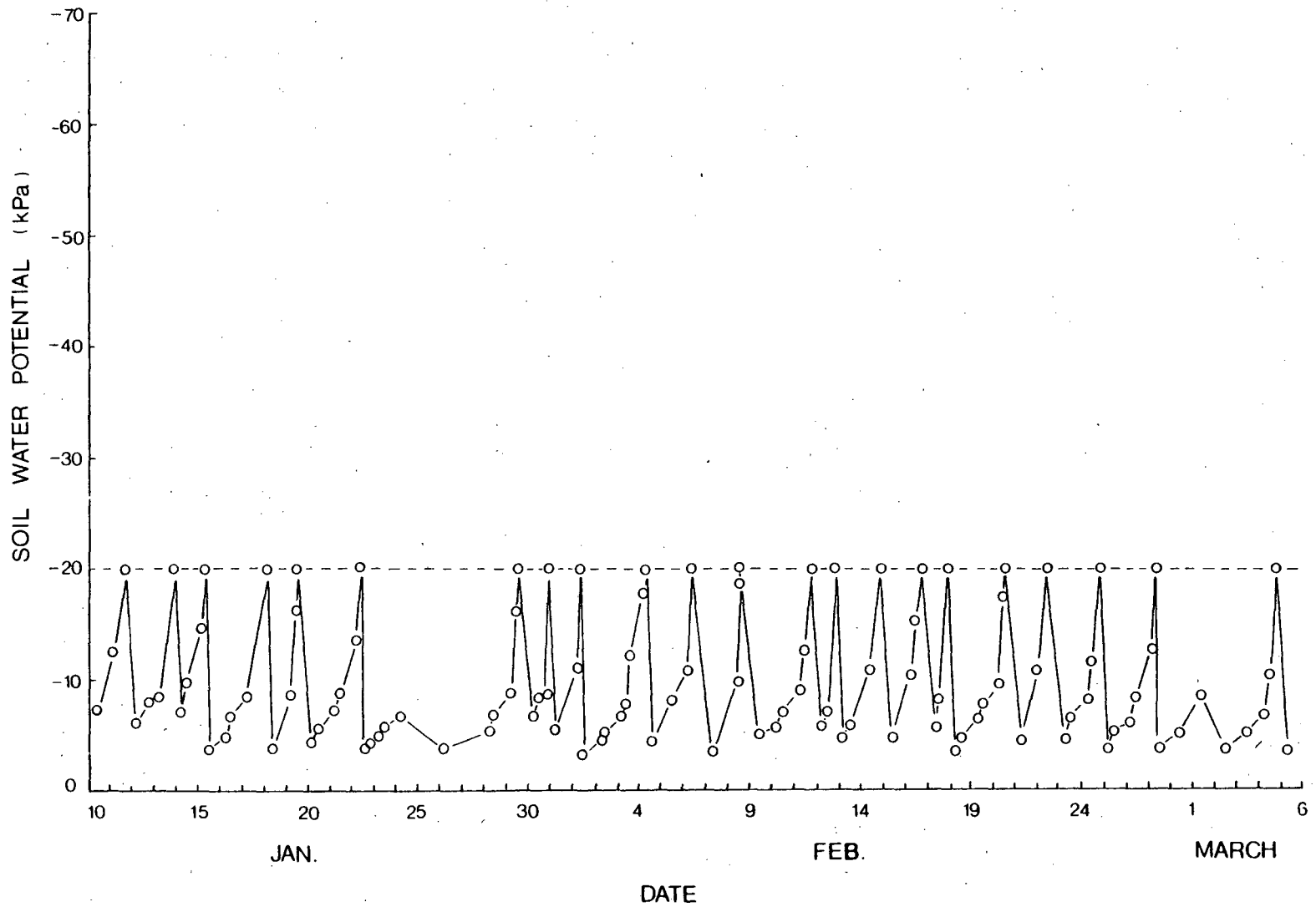
Fig. 6: Variation in soil water potential as a result of consecutive cycles of irrigation and drying at a -20 kPa regime.
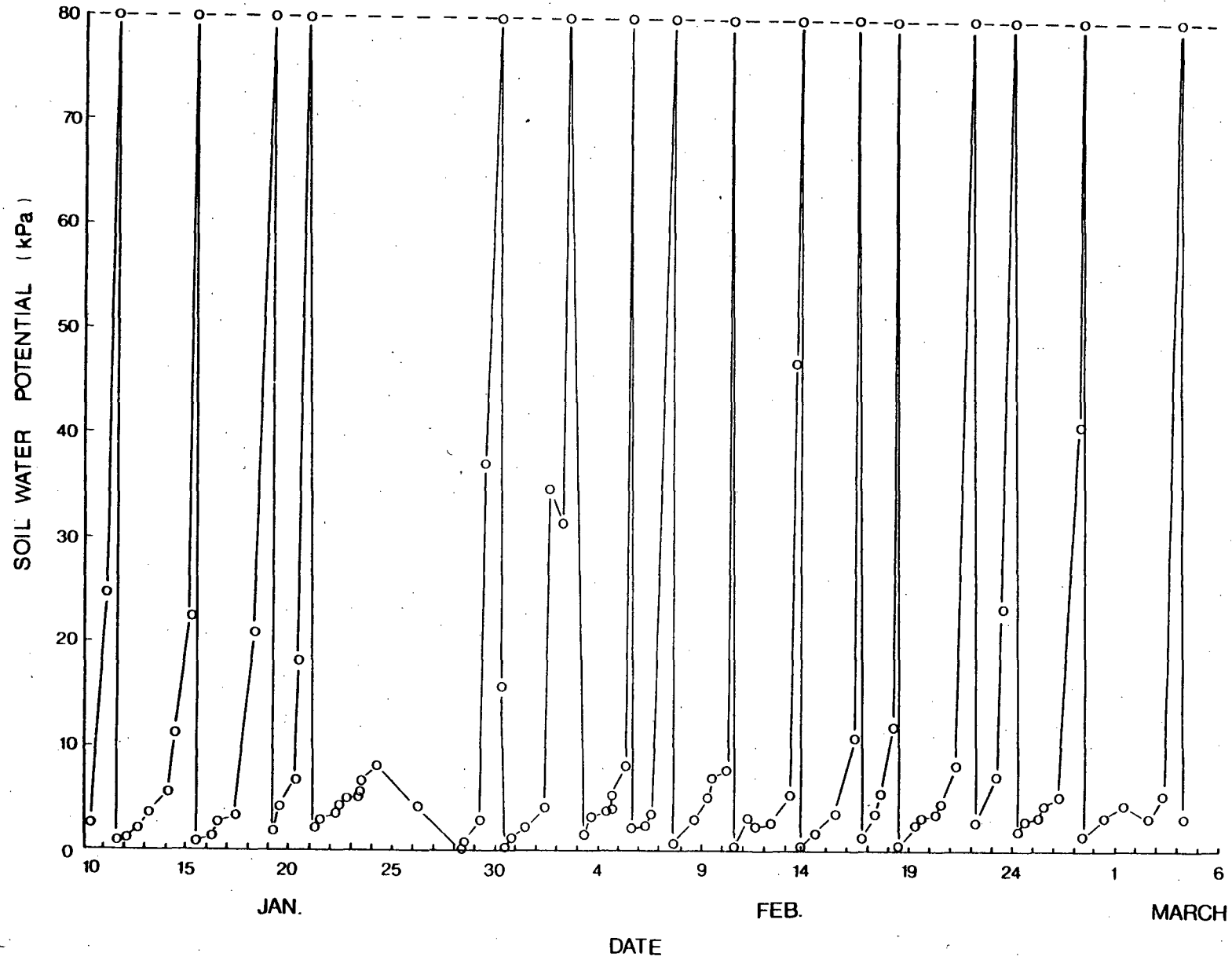
Fig. 7: Variation in soil water potential as a result of consecutive cycles of irrigation and drying at a -80 kPa regime.
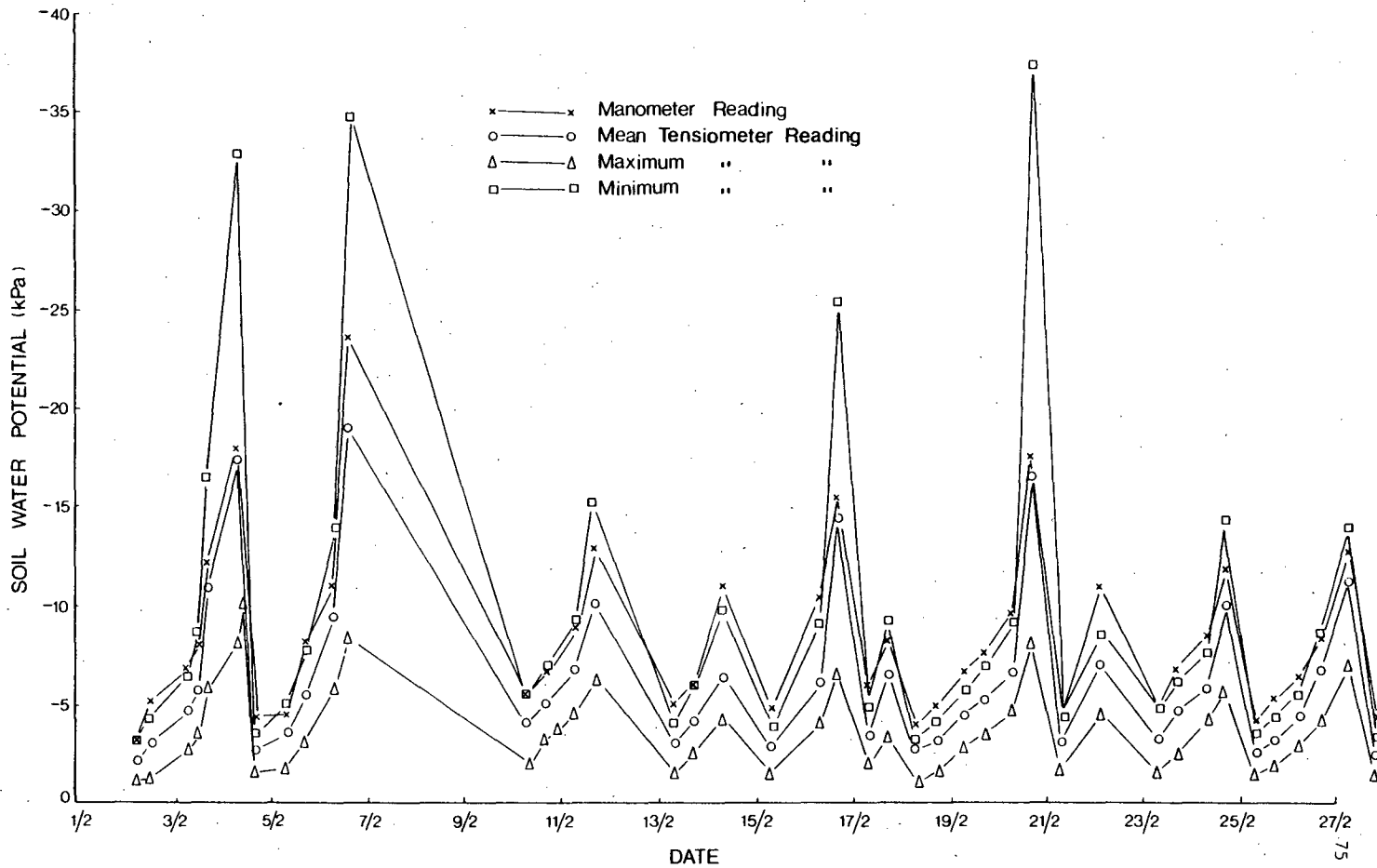
Fig. 8: Comparison between readings obtained from the ceramic cell/manometer and control tensiometers at various depths
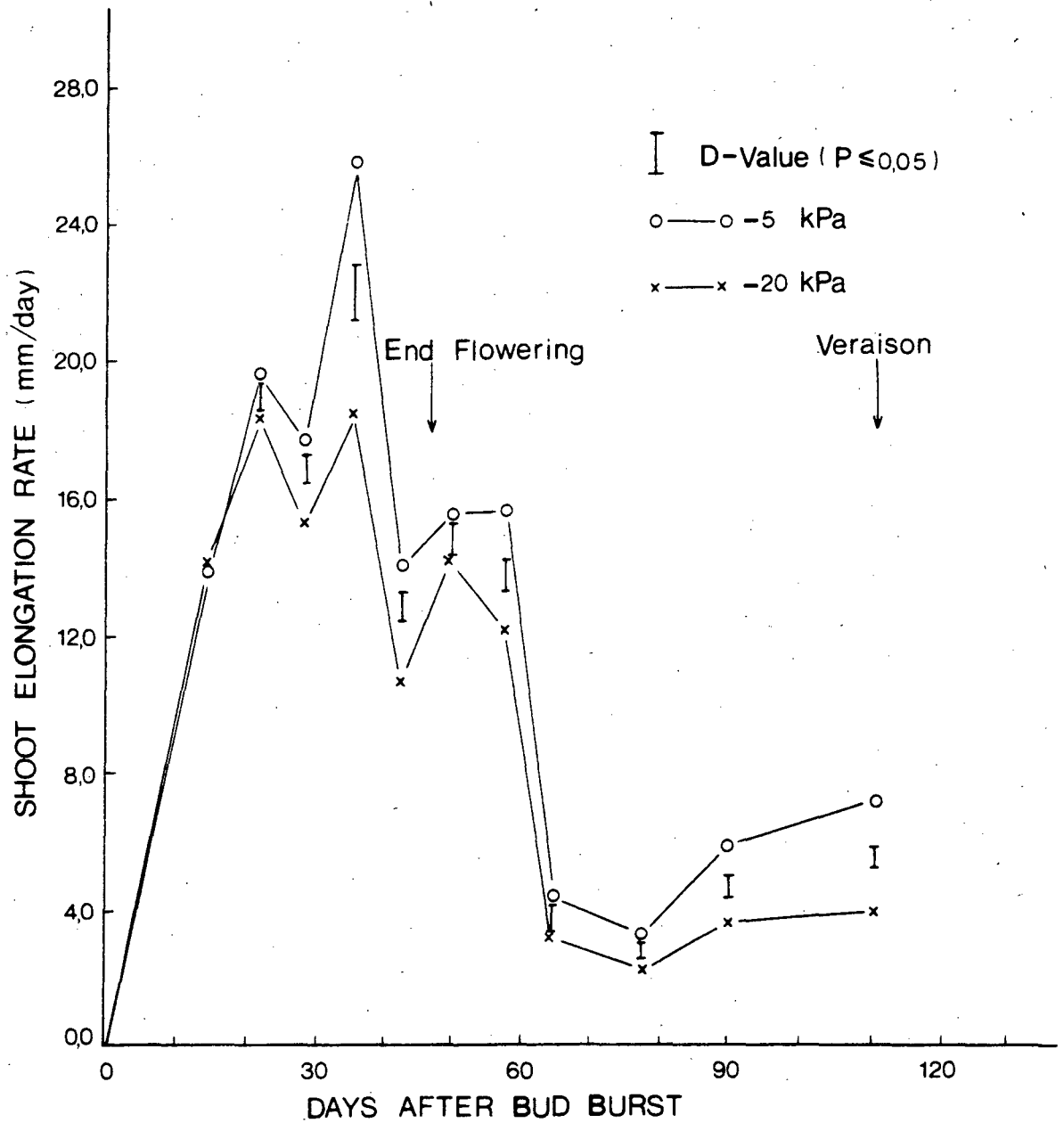
Fig. 9:   Shoot growth rates at two soil water regimes during growth
phases I and II of the grapevines.
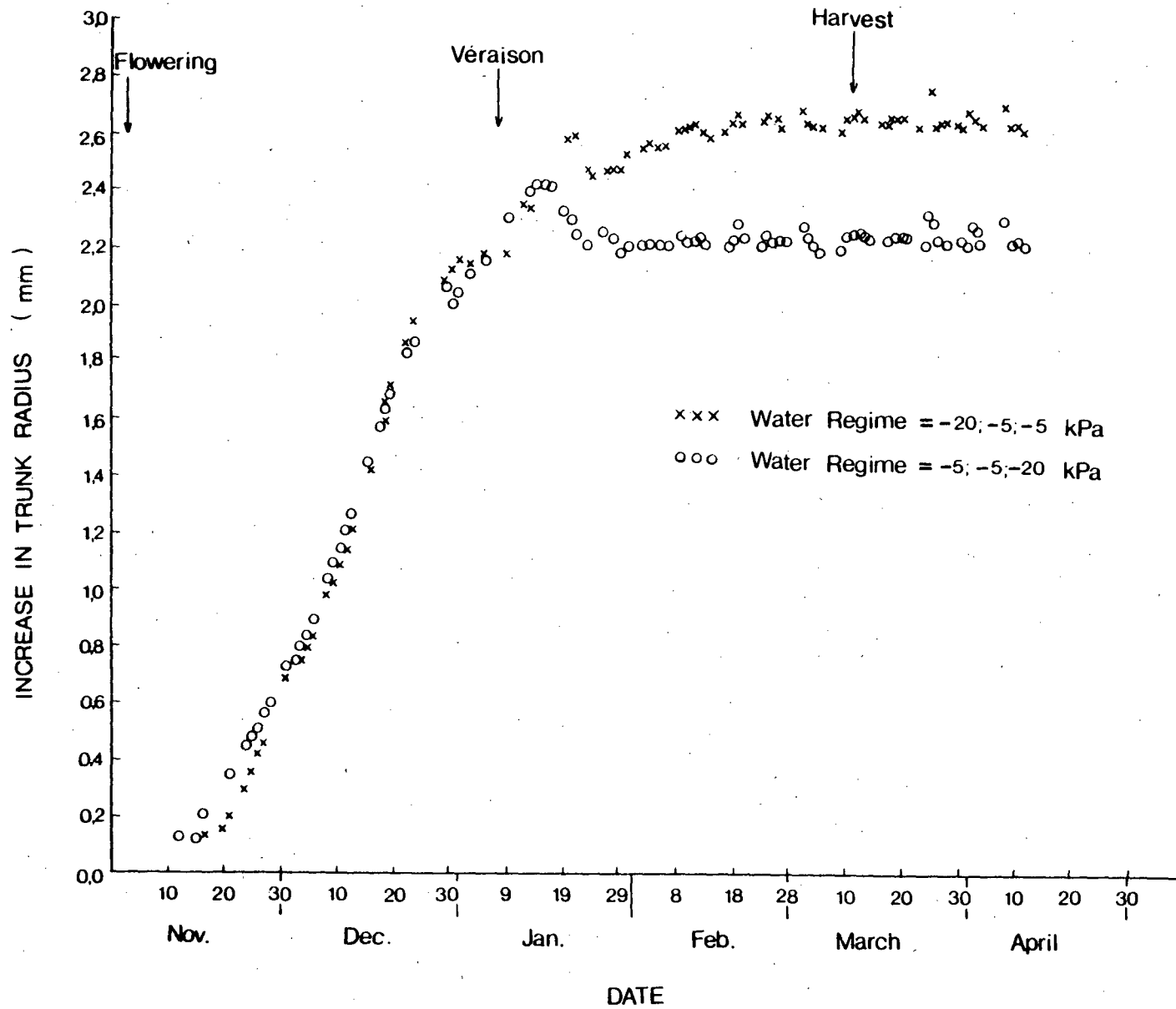
Fig. 10:   Trunk growth of grapevines as measured by dial gauges.
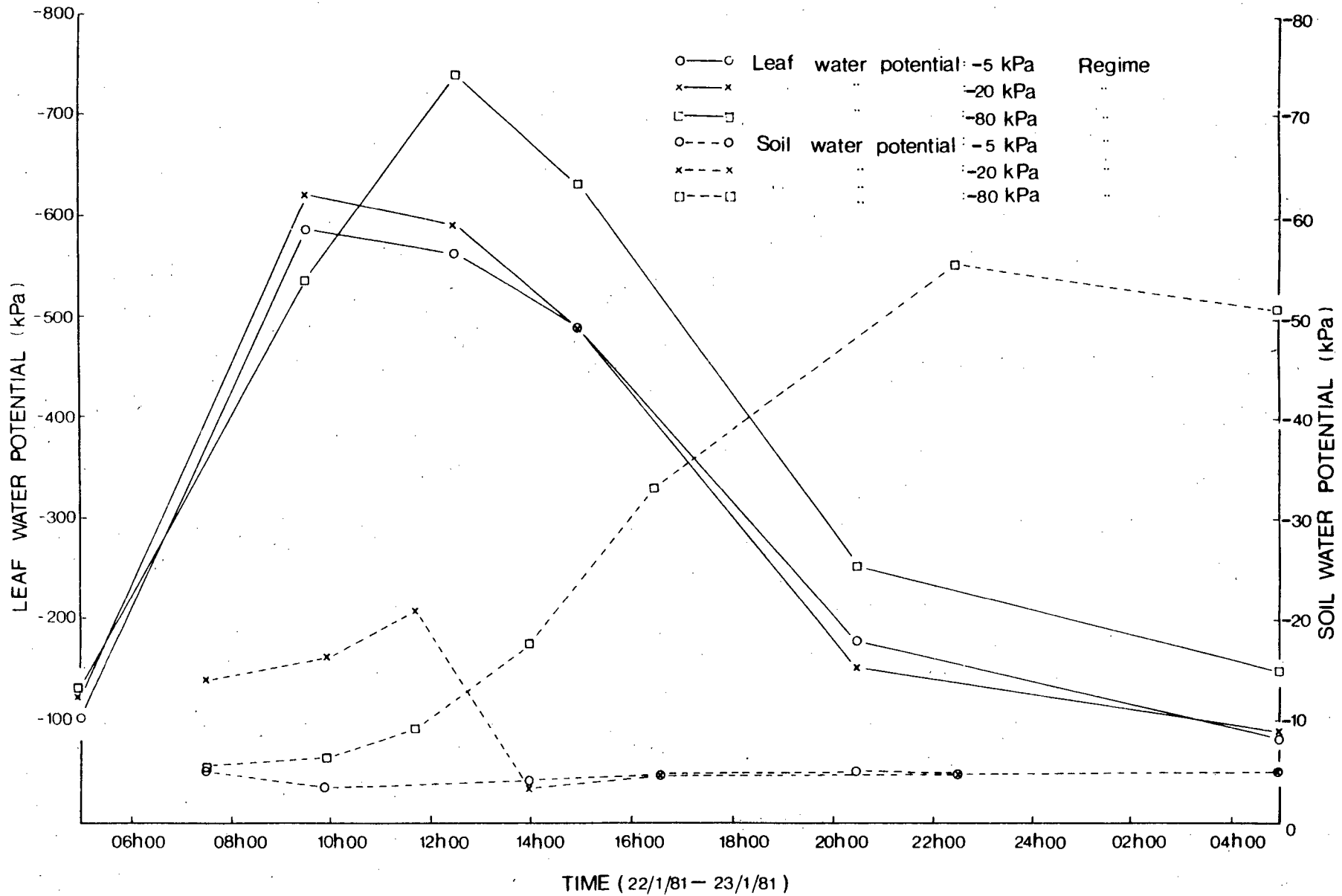
Fig. 11: Variation of leaf water potential and soil water potential at three soil water regimes during a 24 hour period in the ripening stage of the grapevines.

CHAPTER 4

GRAPEVINE RESPONSE IN AN IRRIGATION EXPERIMENT WITH REGARD TO YIELD, GROWTH AND QUALITY PARAMETERS

INTRODUCTION

The irrigation of the grapevine and its response to soil water conditions were reviewed comprehensively by Kasimatis (1967) and recently by Smart & Coombe (1983). Van Zyl (1981) discussed similar aspects against the South African background. Consequently no attempt will be made to elaborate on these publications, but only a few aspects relevant to the present irrigation trial will briefly be discussed.

A summary of 11 research reports world wide showed that pruning mass was increased by irrigation from 4 to 137% over that of non-irrigated controls (Smart & Coombe, 1983). This result closely corresponds to yield increases of up to 130% in the same trials. Most researchers reported an increase in grape yield with increasing irrigation frequency (Branas, 1967; Nijar & Randhawa, 1968; Goldberg & Shmueli, 1971; Smart, Turkington & Evans, 1974; Van Rooyen, Weber & Levin, 1980; McCarthy, Cirami & McCloud, 1983), although a few researchers found the opposite to be true (Tatarenko, 1971; Lombardo, 1972). It is self-evident that results obtained in many of the aforementioned trials are dependent on factors such as climatic conditions and soil type which renders the extrapolation of results doubtful. Few irrigation studies on grapevines related plant response to fundamental parameters such as soil water status as used by Van Rooyen, Weber & Levin (1980) or even crop factors (McCarthy, Cirami & McCloud, 1983).

The phenological stage of the grapevine also determines its responses to

soil moisture stress (Kasimatis, 1967). Consequently researchers have to examine the effect of soil moisture conditions in various phenological stages which are not independent of each other or follow changes and fluctuations of plant parameters in response to soil moisture conditions through the course of a season (Hardie & Considine, 1976; Hofäcker, Alleweldt & Khader, 1976; Van Zyl & Weber, 1977). It was also realized that cultivars differ in their sensitivity to soil moisture regimes as was aptly demonstrated with Aris and Müller-Thürgau (Hofäcker, 1977) and by the effect of irrigation on red wine quality (Rutten, 1977; Freeman, 1978).

The water status of the grapevine can affect grape composition profoundly both directly or indirectly (Smart, 1974; Hidalgo, 1977) and in a positive or negative way depending on the degree as well as the duration of water stress (Amerine, Berg & Cruess, 1972; Hofäcker, 1976; Hofäcker, Alleweldt & Khader, 1976; Fregoni, 1977; Hidalgo, 1977; Hofäcker, 1977; Hardie, 1981). The pertinent question therefore, is how to control water supply to the vine in order to obtain optimum results between the two extremes of over-supply at the one end and severe stress at the other. Knowledge concerning vine response is therefore essential to achieve this objective.

It is generally accepted that a decrease in soil moisture regime yields higher sugar concentrations (Fregoni, 1977; Hidalgo, 1977) but that improper ripening, a lower sugar concentration and poor wine quality, result from severe water stress (Amerine, Berg & Cruess, 1972; Hardie & Considine, 1976; Hidalgo, 1977; Van Zyl, 1981). Research results do not always fit this model as is clearly demonstrated by an increase in sugar concentration with table grapes (Van Rooyen, Weber & Levin, 1980), "no change" results obtained in a pot experiment with Müller-Thurgau (Hofäcker, 1977) and for Chenin blanc under conditions of limited irrigation (Van Zyl & Weber, 1977).

The size of the grape yield does play a role in this respect since it "dilutes" the quantity of sugar produced, which increases with more favourable moisture conditions (Hofäcker, 1976). Results world wide shows an increase in total titratable acidity and malic acid concentrations of grapes under high soil moisture regimes (Hofäcker, Alleweldt & Khader, 1976; Hidalgo, 1977; Hofäcker, 1977; Safran, 1977; Van Zyl & Weber, 1977; Hardie, 1981).

Little information regarding the effect of irrigation systems on grape quality is available. In the United States no difference in sugar and total titratable acidity was found in Ugni blanc (Trebbiano) between trickle, flood and sprinkler irrigation (Peacock et al. 1977). Similarly in Australia tricklers did not affect the sugar/acid ratio, though a difference in harvesting date was experienced (Smart, Turkington & Evans, 1974). Irrigation generally results in later harvesting and in some cases the difference in grape composition by water supply to the vine could be explained on basis of a difference in maturity (Hardie & Considine, 1976; Hidalgo, 1977; Safran, 1977).

The many morphological changes of plants in response to water stress have been reviewed by Turner & Kramer (1980). In the grapevine, shoot elongation rate presents a very sensitive indicator of vine water stress (Vaadia & Kakismatis, 1961; Smart, Turkington & Evans, 1974; Hofäcker, 1977; Van Zyl & Kennedy, 1983) and consequently water supply can greatly affect the size of the vine canopy and therefore the micro-climate around the bunches and eventually grape composition (Kliewer & Schulz, 1964; Kliewer & Antcliff, 1970; Smart, 1974; Safran, 1977). Stem diameter has also been used as an indicator of vine water stress both on a long term basis (Vaadia & Kakismatis, 1961) and for diurnal fluctuations (Smart, 1974). Measurement of stem diameter offers a fairly simple, reasonably accurate and non-

destructive method of indicating water stress but no attempt has been made to actually shedule irrigations according to this parameter.

Roots, being the organs for water uptake, are of special importance in irrigation research. Various methods of studying plant root systems are comprehensively described by Böhm (1979). However, root growth of vines in response to water stress has only rarely been investigated. In a pot experiment with the cultivar Aris, root mass decreased only when the soil water regime was lowered to 25% (Hofäcker, 1977), though in lysimeter studies Van Rooyen, Weber & Levin (1980) found that a high soil moisture regime favoured root growth. Contrary to the general belief, Chenin blanc established under plastic strips which induced favourable moisture conditions, yielded both more and deeper roots compared to a dryland control (Van der Westhuizen, 1980). However, under wet conditions in rhizotron studies, root growth decreased (Freeman & Smart, 1976).

Many of the aforementioned studies were conducted either in pots and lysimeters or in temperate climates, factors which can affect results drastically. The objective of this experiment was to investigate the effect of soil water regimes, irrigation systems and water stress during particular phenological stages, under field conditions and in a hot climate on grape, must and wine quality, and on growth of a few plant organs in order to control irrigation accordingly.

MATERIALS AND METHODS

Soil

An irrigation trial was conducted at Robertson on a red calcareous soil (USDA soil classification : calciorthid Aridisol (Soil Survey Staff, 1975))

classified as partly Hutton (Maitengwe and Shigalo series), but belonging to the Oakleaf form (Letaba series) in other parts of the vineyard. Both soil forms had a duripan in the subsoil which was impenetrable to roots. Consequently the soil was ploughed to a depth of approximately 1m with a delve plough and 1,5 t of a superphosphate applied per ha prior to planting. Although the ploughing depth was less than 1m in some places due to extreme hardness of the duripan, the exact soil depth was determined on each plot after soil preparation. A well defined root zone was thus created since no roots could penetrate below the ploughing depth.

Three years after preparation of the soil, a profile pit was dug on each plot and upon inspection it was decided to subdivide the profile into four layers viz., 0-0,25 m, 0,25-0,50 m, 0,50-0,75 m and 0,75-1,0 m. All measurements and samplings were done at these depths. Soil sampled from all plots were used for a particle size analysis as well as for a chemical analysis which included pH (1,0 M KCl), electrical resistance (saturated paste), extractable cations (1 M NH_4Cl at pH of the soil) as well as P and K (Bray No.2). Bulk density was determined in triplicate using the core method (Blake, 1965).

Experimental Layout and Cultural Methods

The irrigation trial consisted of 12 treatments (Table 1) each replicated 6 times in a randomized block design. Blocks were allotted in a manner which minimised the effect of soil variation. In 1974 Vitis vinifera var. Colombar grafted on 99 Richter was planted in five replicates, but the sixth replicate was planted to the cultivar Chenin blanc/101-14. The latter cultivar is susceptible to bunch rot and was used to assess the effect of irrigation treatments on the incidence of Botrytis cinerea and Rhizopus species.

The planting distance was 3,0 x 1,5 m and the vines trained on a factory system as described by Zeeman (1981). Each plot consisted of 18

experimental vines separated from neighbouring plots by four buffer rows and five buffer vines in the experimental row.

Irrigation were scheduled according to predetermined soil moisture levels (Table 1). A soil moisture regime of 25% meant that 75% of the plant available moisture (PAM) summed over the total rooting depth of 1m was depleted by evapotranspiration (For the purpose of this study PAM was defined as FC minus PWP) before irrigation was applied. These regimes were maintained by regular monitoring of soil water status with the aid of tensiometers, gravimetric soil moisture determinations and the neutron back-scattering method (see Chapter 5 for details).

The twelve treatments (Table 1) can be subdivided into three groups viz.,

(a) Soil moisture regimes (T1 - T4) : These four treatments represented soil water depletion to levels of 25%, 50%, 70% and 90% PAM and were maintained from bud burst to harvesting. Plots in this treatment group were irrigated by micro-jets.

(b) Stress during phenological stages (T5 - T9) : Moisture stress was defined as soil water depletion to 25% PAM during the duration of a particular stage. A 70% moisture regime was maintained during the rest of the season. Under field conditions only the ripening stage required a water application to prevent the soil water content to fall below 25% PAM. Micro-jets were also used for this group of treatments.

(c) Irrigation systems (T4, T10 - T 12) : The four viticulturally most important irrigation systems viz., micro-jets (T4), tricklers (T10), sprinklers (T11) and flood irrigation (T12) were also included in this investigation. Each irrigation system operated at soil water regimes

usually recommended in practice i.e. tricklers and micro-jets at a 90%
regime, but sprinklers and flood irrigation at a 50% soil water regime.
Micro-jets of the type B2 280° were installed upright, 0,3 m above
ground level with a spacing of 3,0m x 3,0m and an application rate of
6,8 mm h^{-1}. This irrigation system wetted the total soil surface
area. Trickle irrigation was applied at a rate of 4 dm^3h^{-1} and
the spacing between tricklers was 1m. Sprinkler irrigation was carried
out using under-vine sprinklers while flood irrigation took place in 2m
wide furrows with the vine rows down the middle. Furrow lengths were
restricted by the lengths of plots i.e. 34,5m. Volumetric valves were
installed on each plot in order to apply the correct quantity of water.

Standard viticultural techniques as regads fertilization, spray programmes
and pruning were applied in the experimental vineyard. A minimum cultiva-
tion practice consisting of growing a cover crop during winter and spraying
it with a herbicide before bud burst was followed in order to leave a layer
of dead organic matter on the soil surface. In some years a second herbi-
cide application was necessary during January to combat weeds like Morning
Glory (Convolvulus arvensis) and burr grass (Setaria verticilliata).

During the first two seasons after planting, the experimental vineyard was
irrigated with an overhead portable sprinkler system. Irrigation treatments
had been applied since 1976/77, but 1977/78 was the first trial season.

Plant Performance

Grape Yield: The fresh mass of grapes was determined for vines individual-
ly, annually at harvesting time. Bunch mass as well as number of bunches
per vine were also determined during two seasons viz., 1980/81 and 1981/82.

Shoot Growth: Pruning mass as an indicator of shoot growth was determined annually during winter time. Shoot lengths were measured on a weekly basis on some treatments to assess the effect of irrigation treatment on shoot elongation. Shoots bearing two bunches and growing in similar positions on lower cordons were selected for this purpose. Measurements commenced when the shoots reached a length of approximately 150mm and continued until véraison after which time damage to the shoot tips prevented further reliable measurements.

Trunk Growth: Trunk circumference was measured annually 0,40 m above ground level at pruning time after loose bark was removed. Self registering dendrographs, attached to the vine trunks were installed in November 1979 on four plots maintained at four soil moisture regimes (T1, T2, T3 and T4). A metal probe pressing against the trunk conveyed diurnal shrinking and swelling of the trunk as well as more long term effects such as growth to a chart. Charts were replaced weekly and measurements continued for three seasons.

Root Studies: Two years after planting, the root distribution of the young vines was investigated by plotting root positions against a profile wall parallel to the vine row and 0,50 m distant from the vine. During the winter of 1979 when the experimental vineyard was in full bearing the root growth pattern during the growing season was studied on four plots maintained at four soil moisture regimes (T1 - T4). This was done with the aid of four root observation chambers consisting of a steel frame covered by wood (Fig. 1). The two opposite sides parallel to the vine rows consisted of 5 mm thick removable glass panels of 300 mm x 300 mm, fitted into galvanised window frames. Inset in the glass panes is a thin wire grid of 12 mm x 12 mm spacing. These chambers were installed between two vine rows in pits, dug slightly larger than the size of the chamber. The soil was back-filled

carefully along the sides of the chambers in the same horizon sequence as before and then allowed to stabilise for one year before root studies commenced. The glass-panelled sides were 0,50 m away from two opposite vines in two adjacent rows. Black plastic sheeting was hung in front of the glass panelled sides to shut out any light. Access to the root chamber was obtained by means of a close fitting trapdoor which was opened only during root investigations. Based upon the above-mentioned precautions and on the report by Böhm (1979) that the temperature fluctuations directly behind the windows generally seemed to be low, it was assumed that root growth behind the glass windows would closely resemble root growth elsewhere in the soil. From the winter of 1980 onwards, root growth was studied weekly in the chambers for two seasons. The number of actively growing root tips against the glass panels were counted as well as the number of intersections between white roots and the wire grid. Root length was calculated using the following equation (Böhm, 1979) :

Root length (mm) = 7,86 x Number of intersections x Grid unit (mm)

Upon completion of the irrigation experiment in the winter of 1983 i.e. after seven years of different irrigation treatments, root distribution was again investigated using the mapping technique as before. Roots were also classified into four groups according to diameter viz.,

< 0,5 mm	=	fine roots
0,5 - 2,0 mm	=	thin roots
2,0 - 5,0 mm	=	medium roots
> 5,0 mm	=	thick roots

This was done on four replicates of Treatments 1, 2, 3, 4 and 10. Additional

to the mapping of roots in a profile wall parallel to the vine row, the root distribution across rows of plots receiving trickle irrigation (T10) and micro-jet irrigation (T4) was also compared.

In order to quantify the nature of the root system, the rooting idex used by Du Pont & Morlat (1980) was adapted to accomodate the root thickness classes employed in the present study. This index was calculated using the formula:

$$\text{Rooting Index} = \frac{R \ (<0,5mm) + R \ (0,5 - 2,0mm)}{R \ (2,0 - 5,0mm) + R \ (>5,0mm)}$$

where,

R = number of roots in the different thickness categories

The rooting index is considered to be a good indicator of soil conditions. A higher rooting index is a reflection of favourable soil conditions which would result in a higher proportion of fine and thin roots relative to thicker roots.

Leaf Analyses

During three of the investigation seasons leaves were sampled from vines at different soil water regimes (T1 - T4) as well as from those irrigated by different irrigation systems (T10 - T12). Three weeks after flowering (Conradie, 1981) leaves were picked opposite the bunches. Petioles were separated from the leaves immediately after picking. Both parts of the leaves were then dried and ground to 70 mesh fineness. Samples for total N were digested with a mixture of sulphuric and selenous acid in glass digestion tubes in an aluminium block and then measured by Auto Analyzer (Auto Analyzer method no. 369 - 75 A/B). Samples for P, K, Ca, Mg and Na were also wet-digested on the Al block with a mixture of nitric and perchloric acid.

Phosphorous, after colour development (Phospho-Molybdate method), was also determined by Auto Analyzer, and K, Ca, Mg and Na by atomic absorption spectrophotometry.

Quality of Grape Juice and Wine

In this experiment the effect of irrigation on quality aspects of wine grapes was investigated through more than one approach. Commencing in 1978, representative grape samples were collected annually from each plot at harvesting which took place on the same date for all treatments since the ideal sugar/acid ratio of 2,5 (Du Plessis, 1977) could not be obtained. Must from these grape samples was analyzed for total soluble solids (TSS), total titratable acidity (TTA) expressed as tartaric acid, and pH. Between 1979/80 and 1981/82 the total N, P and cation concentrations were also determined on these must samples, applying the same methods used for the analyses of leaf samples. In three seasons grapes were also harvested and experimental wine made in 20 dm^3 containers according to standard VORI procedures. In the 1979/80 season, however, grapes for wine making were left on the vines until the 20th of April (three weeks after the rest of the grapes were picked) in an attempt to improve wine quality. Experimental wines were bottled and then judged by a 14 member tasting panel according to the score card system described by Tromp & Conradie (1979).

In the 1981/82 season each irrigation plot was subdivided into three split plots where crop levels of theoretically 100%, 75% and 50% of the actual fruit load were maintained. This was accomplished by counting all the bunches on all plots before bloom and by removing the appropriate number of bunches from 75% and 50% crop level plots respectively, at the end of December in order to try and improve quality of the grapes by lowering the yield. Grapes from all three crop level treatments were sampled for analyses and small scale wine making as described before.

Additional to the must analyses at harvesting Colombar berries were sampled weekly from T1, T2, T3, T4, T6, T8 and T10 vines (Table 1) for three seasons (1978/79 - 1980/81) starting three weeks after full bloom and continuing until maturity. Approximately 200 berries were representatively picked from each treatment plot, their mass and volume determined and after maceration in a mortar, squeezed through cheesecloth and the juice centrifuged at 3000 r.p.m. (centrifugal force = 1 550 x gravity) for 10 minutes. After determination of its pH the juice was immediately analyzed for total soluble solids, using an Abbé refractometer, total acidity by titration with 0,1 M NaOH to a pH of 8,2, tartaric acid (Rebelein, 1973) and malates by an enzymatic method (Anon., 1976).

Incidence of Bunch Rot

The incidence of <u>Botrytis</u> <u>cinerea</u> and sour rot, two main contributers to total bunch rot, were evaluated separately on both Chenin blanc and Colombar in two seasons. In the following three seasons only total bunch rot was determined. These determinations were based on the visual scoring of individual bunches according to a scoring system which included six categories, viz.,

        0 = no visual signs of rot
        1 =   0 - 10% rot
        2 = 10 - 25% rot
        3 = 25 - 50% rot
        4 = 50 - 75% rot
        5 = 75 - 100% rot

Twenty five vines per treatment and 20 bunches per vine were randomly chosen

for this evaluation. The incidence of rot was then determined using the formula of Unterstenhöfer (1963) namely,

$$\text{Rot (\%)} = \frac{(n_0 + n_1 + n_2 + n_3 + n_4 + n_5)}{5 \ (n_0 + n_1 + n_2 + n_3 + n_4 + n_5)} \ \times \ 100$$

where,

   n_i = number of bunches in category i

Statistical Treatment of Data

A standard two-way analysis of variance (Snedecor + Cochran, 1967) was applied to data sets. Additionally, treatments were statistically grouped by performing the Scott-knott test (Gates & Bilbro, 1978). The cumulative grape yield was further analysed using the orthogonal test of planned contrasts (Snedecor & Cochran, 1967). For the application of this test, the 12 irrigation treatments were subdivided into three groups namely,

- soil water regimes (T1 - T4)
- phenological stages (T5 - T9)
- irrigation systems (T10 - T12)

RESULTS AND DISCUSSION

A particle size analysis revealed that the soil in replicates 1-3 contained less clay and silt, but more fine sand than in replicates 4-6 (Table 2). Texturally soil from the first group of replicates can be classified as a sandy loam while soil from the latter group of treatments (4-6) is a sandy clay loam. Bulk densities on the sandy loam soil were also higher (mean ρ b = 1520 kg m^{-3}) than on the more clayey soil (mean ρ b = 1420 kg m^{-3}). As a consequence of the variation in soil form, particle size analysis and

bulk density, the experimental vineyard was divided into two parts with regard to irrigation. Separate irrigation schedules were calculated for replicates 1 - 3 (Maitengwe soil series) and the replicate group 4 - 6 (Shigalo and Letaba soil series).

A chemical soil analysis (Table 3) showed no nutrient deficiencies or unfavourable soil chemical conditions and merely confirmed that the experimental vineyard was planted on a high potential soil.

Grape Yield

The irrigation treatments affected grape yield significantly in only two of the investigation seasons viz., in 1978/79 and 1979/80 (Table 4). The 1978/79 the two treatments T1 and T10 gave the lowest yield, significantly less than T5. In the following season grape yield of the T1 treatment was significantly less than on T4 plots. Cumulative grape yield is a more reliable indicator of yield response to irrigation treatments than values for single seasons. Although neither the Newman - Keuls test nor the Scott-Knott test showed significant differences among treatments (Table 4), the orthogonal test of planned contrasts statistically backed a few of the distinct trends in the cumulatve yield data (Table 5). In the soil water regime group of treatments (T1 - T4) the grape yield was significantly decreased by a 25% regime (T1) compared to the 70% (T3) and 90% regimes (T4). These cumulative yield data were further supported by the results of berry samples which showed significantly smaller berries on T1 than on T2, T3 and T4 plots (see discussion later).

The orthogonal test of contrasts, applied to the cumulative grape yield (Table 5), also indicated significant differences in the treatment group of plots which were stressed during particular phenological stages (T5 - T9).

Grape yields of T6 and T8 decreased significantly relative to those of T5
and T9. The vines performed well without irrigation from bud burst to
flowering (T5). This part of the season was generally cool, leaf areas of
the vines were still small and due to these factors, the vines had a low
irrigation requirement. During the early stage of the season water can be
saved without a deleterious effect on grape yield. However, water stress
during fruit set (T6) caused a drastic decline in grape yield at harvest
even though the stressed plots had been irrigated at a 70% soil water level
from the lag phase of berry growth until harvest. Berry sampling confirmed
this result indicating that water stress damage during the phase of rapid
cell division and enlargement in the berry, is permanent and cannot be recti-
fied. Water stress during the very long (75 - 85 days) and hot ripening
stage (T8) resulted in a significant decrease in grape yield. Berry samples
taken during this stage, indicated that berry size increased with improved
soil water status or vice versa. Water stress applied during the lag phase
of berry growth (T7) also appeared to be detrimental to yield, but this yield
reduction was not statistically proven. In this experiment T9 differed very
little from T3 (70% water regime) with regard to both soil water status and
yield, confirming the favourable response to a 70% soil water regime.

The four irrigation systems compared in this irrigation trial yielded simi-
lar grape masses (Table 5). Apparently on good soil, grapevines can produce
equally high yields under almost any irrigation system if water applications
are scheduled correctly. Furthermore, it again stressed the fact that yield
was not very sensitive to soil water levels between FC and a 50% soil water
regime. It should, however, be borne in mind that this result was obtained
on a deep, high potential soil which buffered the vines well against sudden
changes in soil water status.

In this study the vines of all treatment plots were pruned to the same

number of buds and bear the same number of bunches. Consequently, yield could only have been the result of increased bunch mass. Bunch masses and grape yields, indeed showed similar trends, although significant differences occurred between T9 and T1 in 1980/81 and between T9 and T6 in 1981/82 only with regard to bunch mass.

Pruning Mass

Winter pruning mass as an indicator of shoot growth response to soil water stress is summarised in Table 6. The cumulative values provide a more reliable indication than data for individual years, which were not always consistent.

Soil Water Regimes (T1 - T4) : The cumulative pruning mass of the 25% soil water regime (T1) was significantly lower than that of the 90% regime (T4) and was separated from the 50% (T2), 70% (T3) and 90% (T4) soil water regimes by the Scott-Knott cluster analysis method (Gates & Bilbro, 1978). Although not statistically significant, the 50% soil water regime displayed a reduction in pruning mass compared to the two wetter treatments in this group.

Phenological Stages (T5 - T9) : Water stress during the lag phase of berry growth (T7) and during the ripening stage (T8) decreased the pruning mass significantly. Similar to its effect on grape yield, T5 and T9 gave rise to high pruning masses. The effect of water stress during fruit set (T6) on shoot growth varied much during the six years under investigation and differed in only two years significantly from T7 and T8. Water stress on T6 plots coincided with high shoot growth rates (Fig. 2), but regrowth started again with resumption of a high irrigation frequency.

Irrigation Systems (T4, T10 - T12): Trickle irrigation resulted in a lower pruning mass than any of the other irrigation systems in most of the trial seasons and especially when cumulative data are used. A reduction in growth in this irrigation trial was not necessarily a negative effect, because many of the treatments induced a too luxurious vegetative growth unfavourable for high grape quality and conducive to fungal diseases. However, on shallow less fertile soils, irrigation practices which lead to an increase in pruning mass will be desirable.

Yield/Pruning Mass Ratio

Zeeman (1984, Personal Communication) proposed a yield/pruning mass ratio of 6-8 for wine grapes trellised on a factory system at Robertson. The yield/ pruning mass ratios (Table 7) of all treatment plots except T1 and T10, fitted Zeeman's ideal balance between fruit and foliage. The latter two treatments yielded higher ratios which suggested too much crop for the shoot growth.

Shoot Elongation

Shoot elongation rates for a few irrigation treatments are presented in Fig. 2. Corresponding to the results of other seasons, T4 and T3 vines yielded relatively similar shoot elongation rates. These rates were significantly higher than that of T1 (25% soil moisture regime). Results for T2 vines (50% soil moisture regime) which did not differ from any of the other treatments in this respect, are in accord with those of other seasons and also correspond with trunk circumference data (Fig. 3). The shoot elongation rates of T6 vines which were only stressed during bloom and phase I of berry growth, immediately responded to the decreasing soil water content and were already significantly lower than those of the T3 and T4

vines by the middle of November. These data clearly illustrate that shoot elongation rate is sensitive to water stress and can be manipulated by irrigation. Results obtained in pot experiments (see Chapter 3) showed an even more marked effect of moisture stress on shoot elongation rate.

Trunk Growth

Trunk circumference and diurnal trunk movement have been used by researchers to assess vine response to irrigation treatments (Vaadia & Kasimatis, 1961; Smart, 1974). Trunk circumferences of the four irrigation regimes (T1 - T4) tested in this trial are depicted in Fig. 3. Trunks of T1 were significantly thinner than those of T3 and T4 both of which had comparable values. Trunk circumference of the T2 vines assumed the expected position relative to the others although not significantly different from them.

The growth rate of vine trunks increased from budding and reached a peak at the end of October, remained high till December, but dropped sharply to a negative value at the end of December (Fig. 4). This negative growth rate during ripening was measured in two seasons and indicated a decrease in trunk diameter. The coincidence of decrease in trunk diameter with véraison however, suggest that the grapes themselves may be involved. Measurements also suggest, though not conclusively, that trunks decrease in thickness at bud burst, probably for the same reason as stated above.

In this study there could not be differentiated among treatments with regard to either weekly trunk growth rate or diurnal change in trunk diameter respectively due to a lack of replicates and insensitivity of the dendographs.

Root Studies

<u>Glass Wall Method</u>: The number of actively growing root tips as well as the root length followed the same general pattern during the course of the season and were found suitable parameters for quantifying new root growth. Formation of new roots in both years under investigation reached maxima in the flowering and post harvest period of the vineyard (Fig. 5), therefore confirming findings in pot experiments (Conradie, 1980), in lysimeters (Van Rooyen, Weber & Levin, 1980) and in a rhizotron, (Freeman & Smart, 1975). Irrespective of soil moisture regime, very little new root growth occurred before and at the time of bud burst and surprisingly, also during mid-summer (December till February) when water uptake reached a maximum. White unsuberised roots are therefore not the only pathway for water movement from soil to vine. In one of the investigation seasons (1981/82), the postharvest peak of root growth actually commenced before the grapes were harvested, indicating either that removal of the fruit load was not the only stimulus or that the grapes had already stopped to be the main accumulator of photosynthetic products at that stage.

Significantly fewer active growing root tips were counted in the soil of the driest treatment (T1), in both years in comparison with the other three irrigation treatments, among which the 50% moisture regime (T2) had more actively growing root tips than the T4 plots (90% moisture regime) in 1981/82 (Fig. 6). However, when the total length of unsuberised white roots is compared, only T1 had a significantly lower value than the other treatments due to the fact that the white unsuberised length per root was more on T1 and T4 plots than on T2 and T3 plots. No explanation can be given for the atypically high values of new root growth for T3 vines in November and December 1981 when compared to those of the previous seasons or to the other treatments in the same season.

On average, new root growth in terms of growing tips occurred mainly in the

soil layers nearest to the soil surface viz., 50-45% in the 0-0,30 m soil layer, 34 - 35% in the 0,30 - 0,60 m layer and 21 - 25% at the 0,60 - 0,90 m soil depth. This distribution neither fits the dry (T1) nor the wet (T4) irrigation treatment. For both these treatments the second horizon contained the largest number of actively growing tips, most probably due to too dry or too wet conditions near the soil surface for T1 and T4 respectively. Total white unsuberised root length did not differ significantly among depths when irrigation treatments were grouped together, though for the treatments individually the 0 - 0,30 m soil layer of the T2 plot contained a significantly greater length of these roots than at a 0,60 - 0,90 m depth.

Profile Wall Method

Root studies by the profile wall method two years after planting revealed roots down to the maximum working depth of the delve plough viz., 1,0m. This observation lent further support to the use of 1,0 m as the lower boundary in calculating irrigation quantities.

Root studies in the final stage of the experiment clearly showed that by far the greatest number of roots had a diameter of < 0,05mm. Attempts at comparing the root distribution data statistically failed because of a very high coefficient of variance. This was especially evident when using specific thickness classes as a basis for comparison. It was therefore decided to compare depths and different irrigation treatments in terms of total number of roots and the rooting index only, and to interpret the figures without statistical backing. Both the total number of roots as well as the rooting index was lowest in the upper soil layer (0 - 0,25m) for the four treatments used in the root investigation (Fig. 7). A uniform number of roots of all thickness classes were found between 0,25 - 1,00m. The rooting index increased with depth - T4 being the exception - indicating a more effective root system in the deeper soil layers.

A comparison of the four irrigation treatments (Fig. 8) clearly showed the smallest number of roots on the T1 plots (25% regime) and the largest number on T2 vines (50% regime) which agreed with the finding in the root observation chamber. Vines irrigated by tricklers (T10) had the same number of roots as those watered by micro-jets (T4). The rooting index, however, ranked the four irrigation treatments as follows T1 = T4 < T10 < T2.

The between -row root distribution differed markedly between plots irrigated either by micro-jet or by tricklers. Although the total number of roots were the same for both irrigation systems, 65% of the roots was concentrated 0,50 m from the tricklers and the percentage decreased rapidly towards the middle of the row (Fig. 9). This root distribution was closely related to the wetting pattern under the tricklers. The sphere of wet soil had a diameter of 1 metre. Roots found in the central areas between rows were still alive despite the fact that the soil dried out completely during summer. This observation is supported by work which showed that normal polar transport of water in young apple trees progressively changes to a lateral transport system as the soil in part of the root zone dries to water potentials less than - 100 kPa. (Black, 1976). Black (1976) also reasoned that the minimum size of the wetting pattern should be such that 25% of the root system is supplied with water when converting a mature tree from total surface wetting to trickle since the roots will proliferate rapidly in the wetted zone. In this irrigation trial vine roots which survived in the dry soil were able to extract water again from the middle of the row during spring after the winter rains.

The horizontal root distribution under micro-jet irrigation (Fig. 9) was much more uniform than under tricklers. The root distribution therefore

indicated a lower rooting density and better utilisation of the soil volume. The root distribution under the tricklers suggests a higher sensitivity to drought due to the high rooting density in the wetted soil volume. According to Denmead & Shaw (1962) an effective hydraulic gradient cannot become established between a root and the soil between roots. The total soil volume will rapidly reach wilting point in contrast to a more sparse system in the case of which water use will be limited by decreasing movement of water under ever decreasing levels of unsaturated hydraulic conductivity. A plot of the rooting index (Fig. 10) further clearly shows a high proportion of fine roots i.e. possibly more effective roots, close to the tricklers than further away.

Leaf Analysis

Results from leaf analyses over a period of three years fell well within the limits for wine grapes (Saayman, 1981) proving that the macro-nutrient status of the vines was not a limiting factor in this trial. Analyses of the leaf blades showed no difference among the four irrigation regimes (T1 - T4) in any of the three investigation seasons with regard to the six elements determined (Tables 8, 9 & 10). In 1980/81 when leaves from plots irrigated by different systems (Table 10) were also analysed, sprinkle irrigation yielded the highest K concentration in the blades; significantly higher than those of T1 and T2. There was however, no difference in K concentration among the four comparable irrigation systems i.e. T4, T10, T11 and T12. The Na concentration in leaf blades from sprinkler plots was also significantly higher than in those of all other treatment plots.

Petiole analyses yielded significant results in 1978/79 and 1980/81 but not in the 1979/80 season. In the first season the Na concentration was higher and the Ca concentration lower in T1 than in T3 and T4 petioles (Table 8)

while the Mg concentration in T1 petioles was higher than T2 and T4 figures. In 1980/81 the K concentration in petioles from T1 plots surpassed that of the two wetter moisture regimes (T2 and T3). A comparison among irrigation systems revealed the lowest K concentration from trickler (T10) and flood (T12) plots and the highest concentration from micro-jet plots (T4). The effect of irrigation treatments on K concentration in the petioles can be explained by soil leaching which should be higher under trickle and flood irrigation than under micro-jets and sprinklers. The Na concentration was significantly higher in petioles from sprinkler plots (T11) than in petioles from vines on T12 (flood irrigation), T2 (50% regime) and T3 plots (70% regime).

Berry Samples

For ease of interpretation results for only one representative season and a limited number of treatments are presented (Figs. 11, 12, 13, 14, 15 & 16). Irrigation treatments affected physical berry development greatly in all four years of berry sampling as illustrated by the cumulative berry mass for 1979/80 (Fig. 11). The increase in fresh mass as well as volume of berries followed the typical double sigmoid growth curve of grapes and other fleshy fruit (Winkler et al. 1974; Coombe, 1976; Alleweldt, 1977). A soil moisture regime of 25% (T1) yielded smaller berries than all the other treatments in all years. No differences in berry size or mass were found among a 90% (T4), 70% (T3) and 50% (T2) soil moisture regime or between trickle irrigation (T10) and micro-jets (T4) (Table 11).

Stressing the vines during flowering and fruit set (T6) reduced berry mass significantly (T4 serves as control) and although water applications continued again in the lag phase (phase II) of berry development, berries of this treatment remained small till the end of the season. According to literature moisture stress during this critical berry growth stage (phase I)

limits cell division, a limitation which cannot be rectified by favourable moisture conditions at a later stage. In this study, fruit set (number of berries which developed in relation to number of flowers) was negatively affected by a dry soil moisture regime (results not shown) in accord with findings of Alexander (1964) and Hofäcker (1976).

Moisture stress during the ripening stage (T8) had a deleterious effect on berry mass in one season only when compared to T2, T3 and T4, but from observations and results obtained in some individual weeks, it became clear that shrinkage of berries does occur in this stage if irrigations are not scheduled carefully. Berry mass is however, not nearly as sensitive to moisture stress in the ripening period as in the cell division phase.

With regard to sugar concentration the driest treatment (T1) and the trickler treatment (T10) were exceptions, having resulted in significantly higher values than the other treatments (Fig. 12). This result can be ascribed to various reasons. Plots of T1 not only produced small berries, but also yielded a low shoot growth which permitted sunlight to penetrate much better to the bunches, with a higher temperature, beneficial to sugar accumulation as a result. Water stress during ripening (T8) significantly enhanced sugar concentration during one of the trial seasons. Berry shrinkage could have played a role in this result since a decrease in photosynthetic activity in T8 vines was measured towards the dry end of this soil moisture regime (see Chapter 6). Small berries in the case of the T6 vines did not contribute to an increase in sugar concentration while soil moisture content in the range 50 - 90% PAM (T2, T3 and T4) did not affect sugar concentration.

The TTA concentration was highest in T4 and T2 berries and it decreased significantly with water stress at phase I of berry growth (T6) and during

ripening (T8). Berries from T1 and T10 plots were, however, lowest in TTA compared to all other treatments in 1979/80 (Fig. 13 & Table 11). In this season grapes from the two latter treatments were harvested three weeks earlier than those of their counterparts due to a more favourable sugar/acid ratio. The rate of decrease was also most rapid in T1-grapes after véraison.

The highest tartrate concentration was found in grapes from the dry treatment (T1) and in T6 grapes which were stressed during bloom and the cell division period (Fig. 14). Although the decrease in tartaric acid took place at the fastest rate in T1 grapes, no difference existed at harvest. Tartrate concentration became fairly constant early in the season in Colombar, irrespective of irrigation treatment in all seasons, contributing to the very slow rate of TTA decrease towards harvesting.

From véraison onwards malate concentrations of trickler (T10) and dry treatment plots (T1) were significantly lower than those of the other irrigation treatments (Fig. 15). These differences may be due to the micro-climate inside the vine canopy as affected by shoot growth. The slow decrease in TTA towards the end of the season can largely be attributed to malic acid decomposition which continued till harvesting. The tartrate/malate ratio was highest in the trickler (T10) and dry treatment (T1) and lowest in grapes grown at higher soil moisture regimes (T2, T3 and T4) with values ranging from 2,58 - 1,50 at harvesting (Fig. 16).

The pH of the must did not differ significantly among treatments in the 1979/80 season (Table 11), but T1 berries showed a tendency, substantiated statistically in other seasons, towards a higher pH than the other irrigation treatments. Trickle irrigation had no significant effect on the pH of the juice compared to the other irrigation systems.

Must Analyses

Mean results of must analyses of Colombar grapes at harvesting obtained over a six year period for all twelve treatments are presented in Table 12. The range between the highest and lowest values of TSS, TTA, sugar/acid ratio and pH was surprisingly small. It is also strikingly evident from the treatment ranking that those treatments which were distinctively different in the analyses of berry samples viz., T8 (stress during ripening), T10 (trickle irrigation) and T1 (driest treatment), are on top of the TSS list, had the lowest TTA values and the highest sugar/acid ratios (together with T7).

Comparing results obtained for each parameter presented in Table 12 no differences existed among the 50%, 70% and 90% moisture regimes (T2 - T4), but T1 vines showed significantly higher TSS, lower TTA values and a more favourable sugar/acid ratio than its three counterparts. The pH values of all 12 irrigation treatments did not differ statistically.

A comparison of irrigation systems viz., micro-jets (T4), tricklers (T10), sprinklers (T11) and flood (T12) statistically by the Scott-Knott test (Gates & Bilbro, 1978), showed trickle irrigation to have a more favourable effect on must quality than the other irrigation systems. Sprinkler irrigation (T11) were rather similar to micro-jets (T4) with regard to TSS, TTA and sugar/acid ratio. Flood irrigation performed better i.e. higher TSS, lower TTA and a higher sugar/acid ratio than both the two latter treatments but not as well as trickle irrigation (T10).

In this study the effect of moisture stress during specific growth stages of the vines (T5 - T9) was significantly the highest on T8 (stress during ripening) and the least so on T6 vines (stress during fruit set), the

difference between those two treatments being significant with regard to all parameters measured in the must, except pH. The reason for the low TSS value and unfavourable sugar/acid ratio on T6 grapes is not clear since this treatment yielded small berries (Fig. 11) which theoretically would have been beneficial to a high sugar concentration. Treatment 7, stressed during the lag phase of berry growth performed well, differing from T8 (which gave best must quality) with regard to TSS concentration only. Moisture stress in the period bud burst to flowering (T5) assumed an intermediate position among this group of treatments, not having a particular favourable or dele- terious effect on wine quality.

Results of must analyses for Chenin blanc grown at four irrigation regimes (Table 13) showed a much more prominent response to soil moisture conditions than those for Colombar e.g. a 2,82 g dm^{-3} difference in TTA between T1 and T4 measured for Chenin blanc in comparison with only 0,72 g dm^{-3} for Colombar. Apparently Chenin blanc is much more sensitive to irrigation ef- fects on must quality than Colombar. The small effect of irrigation on the must quality of Colombar (Table 12) would have been much more pronounced with a more sensitive grape cultivar.

Chenin blanc grapes from T3 and T4 plots (Table 13) had a significantly lower TSS concentration than those from T1 and T2 plots. The TTA concentra- tion of T4 grapes was significantly higher than that of T3 and TTA values for both the latter treatments surpassed that of T1 and T2. The sugar/acid ratio decreased in this cultivar with an increase in soil moisture regime as follows :

T4 < T3 < T2 = T1.

Mineral Elements in the Must

From a wine quality point of view N and K are the most important elements in the must. Agenbach (1977) found that a minimum of 130 mg dm^{-3} assimilable N was needed for successful fermentation of must containing 200 to 230g of reducing sugar per dm^3. Further increases of N increased the fermentation rate. White wine quality in South Africa also improved with increasing N content of the must (Vos, Zeeman & Heymann, 1978; Tromp, 1984).

Potassium affects pH, anthocyanin ionisation and consequently wine colour (Somers, 1977; Hardie, 1981). Generally, low K concentrations in the must are desirable.

The total N concentration in must from trickler plots was significantly lower than that from most other plots in the 1979/80 season (Table 14), but still well above the critical level for fermentation. This result can be attributed to broadcasting of fertilizer and leaching under the tricklers. Changing over to strip fertilization under the vine rows eliminated the problem as is evident from N figures in 1981/82 (Table 15).

Potassium concentrations in the must were not much affected by any of the irrigation treatments in 1980/81 (Table 16) - the lowest values were determined on must from T1 (dry treatment) and T12 (flood) plots. In 1981/82 K concentrations in must from trickle plots (T10) and the driest treatment (T1) were lowest, though the difference was only significant when compared to T9 (Table 15). Potassium also increased with increasing moisture regime from T1 - T4. This result is in agreement with findings of other researchers who found an increase in K concentration of the must with irrigation (Hardie, 1981; McCarthy, Cirami & McCloud, 1983).

Significant differences did also occur among treatments with regard to P and Mg. However, the importance of these differences to wine quality are unknown and it was furthermore not the same treatment which affected P and Mg in the various investigation seasons. Na and Ca were not affected by the treatments in any season.

Wine Quality

Experimental wines made from Colombar grapes in this trial had a very mediocre quality with no significant difference among treatments when mean figures for the various seasons are calculated (Table 17). This can be ascribed to the fact that the grapes did not obtain the desired sugar/acid ratio of 2,5 even when left on the vines until the 20th of April in one season. Members of the tasting panel remarked on the imbalance and high acidity of the wine as the most important reason for the low scoring.

Arguing that the poor wine quality and unfavourable grape composition were related to high grape yields, three crop levels were tested. The actual grape yields obtained in the crop level experiment differed significantly (Table 18) resulting in a 100%, 70% and 49% crop load. However, despite the drastic decrease in yield, the masses of bunches and berries were maintained at the same level. Subdividing the irrigation plots by introducing three crop levels had absolutely no effect on TSS and TTA of the grapes and accordingly also not on the wine. On the contrary, a tendency existed for the highest crop level to yield the best wine quality (Table 18) although these differences were not significant. The inability to change grape composition by different crop levels again points to the insensitivity of Colombar which can be either detrimental or advantageous depending on the circumstances. It does also point to the fact that grape quality is not dependent on crop level alone, but also on plant size (Branas, 1974).

Bunch Rot :

Water stress during the ripening stage of Chenin blanc (T8) reduced the
incidence of both Botrytis cinerea and sour rot significantly and consis-
tently in two seasons (Table 19). Among the four moisture regime treatments
(T1 - T4) a 25% regime caused the lowest percentage total bunch rot in
1978/79 due to a favourable low incidence of sour rot in this treatment.
Sour rot also occurred less in T1 and T2 plots than in grapes of T3 and T4
during the second season. The pattern was less clear regarding Botrytis
cinerea. The very high incidence of Botrytis cinerea in grapes stressed at
flowering (T6) in 1978/79 seemed to be a coincidence, since this result was
neither repeated during the next season nor in any other season with Colom-
bar.

In the investigation on Colombar a lower percentage of total bunch rot was
found on plots of the 25% water regime (T1) than on those of the three wet-
ter regimes in the three consecutive seasons starting with 1978/79 (Table
20). The incidence of total bunch rot was the same among the latter three
treatments (T2, T3, & T4). This pattern for the four soil water regime
treatments (T1 - T4) was also evident with regard to botrytis and sour rot.
Similar to T1, water stress during the ripening stage (T6) yielded a lower
incidence of total bunch rot than the 50%, 70% and 90% water regimes in the
first two seasons. Results of 1980/81 were undecisive due to untimely heavy
rains during the ripening period, while bunch rot was almost totally absent
in 1982/83, eliminating irrigation effects.

Irrigation treatments in this trial did not wet the grapes. Increases of
bunch rot on certain treatment plots were therefore most probably caused by
a change in micro-climate due to dense canopies and a wet soil surface, as
well as by bigger berries and more compact bunches. Irrigation practices

which enhances these abovementioned conditions together with wetting of the grapes, will undoubtedly be the most favourable for bunch rot.

CONCLUSION

Over a period of six years the cumulative grape yield was significantly reduced by irrigating at a 25% soil water regime compared to soil water regimes of 70% and 90%. However, grape yield did not decrease significantly at a 50% regime. Berry size was also detrimentally affected by a 25% soil water regime maintained throughout the season as well as during phase I of berry growth only. High soil water regimes before flowering and after phase I of berry growth had passed, could not rectify the negative effect of water stress on berry size during flowering, fruit set and the cell division stage. This result was confirmed by the cumulative grape yield reduction as a result of water stress during phase I of berry growth. Maintenance of a 25% soil water regime during the ripening phase, also led to a significant decrease in the cumulative grape yield compared to a 70% soil water regime (control) throughout the season. Irrigation systems had no effect on yield.

Vegetative indicators of vine water stress viz., pruning mass, shoot elongation rate and trunk circumference were all significantly reduced at a 25% soil water regime in comparison with 70% and 90% regimes. These parameters of vines maintained at a 50% soil water regime, assumed an intermediate position between those of the dry and the two wettest regimes. Trickle irrigation led to a decrease in pruning mass in comparison with micro-jets, sprinklers and flood irrigation.

Root growth studied in situ in root chambers in the vineyard displayed two distinct peaks of growth i.e. in spring and during the post-harvest period.

In mid-summer, root growth was at a low level and water uptake occurred mainly through mature roots. Indications were that factors other than crop removal alone stimulated root growth in autumn. Root mapping by the profile wall method revealed a very uniform root distribution with soil depth. In the case of tricklers the majority of roots was confined to the wetted zone, but roots outside this wet area remained alive and extracted water from the soil after spring rains.

The driest irrigation treatments (25% soil water regimes either during the entire season or during the ripening stage only) as well as trickle irrigation, resulted in the highest sugar concentrations and the lowest TTA. Frequent irrigations increased the TTA, and analyses of berry samples showed malic acid to be the most affected. Tartaric acid reached the highest values in dry treatments at véraison, but differences among treatments disappeared towards harvesting.

Chenin blanc was more sensitive to soil water regimes than Colombar with regard to quality parameters, but the general tendency was the same in both cultivars. The wet 90% and 70% soil water regimes gave rise to lower sugar concentrations and higher TTA than the 50% and 25% regimes. Organoleptic wine quality as determined by a tasting panel, did not differ among treatments.

A low soil water regime of 25% during the whole season reduced the incidence of total bunch rot both in Chenin blanc and in Colombar compared to the three wetter soil water regimes. The same favourable result was obtained by applying water stress during the ripening stage only.

Perusal of growth rates of vine shoots, trunks and berries (Fig. 17) as well as sugar and acid concentrations of berries within the course of a season,

clearly shows maxima and low values at different parts of the season for the
various parameters. Since it has been proven that irrigation can affect
each of these parameters individually, it can be anticipated that judicious
irrigation management could be used as a powerful tool to suppress unneces-
sary and even harmful growth and to improve growth of fruit and quality as-
pects. Chalmers, Mitchell & Van Heek (1981) succeeded in obtaining this re-
sult in an experiment with peaches. A prerequisite to make regulated irri-
gation really effective would require management systems that concentrate
root systems such as limited wetted zones as in trickle irrigation, natural
(or even artificial) barriers such as in shallow soils, and dense planting.
Large soil reservoirs such as provided by deep medium textured soils, put
too much water at the disposal of the plant to respond quickly to irrigation
strategy.

Shoot growth can be suppressed by limiting irrigation in the period bud
burst to flowering. Root growth, which also shows a peak in this stage,
will not be unduly decreased by such a schedule since a large part of root
growth occurs after harvesting and it is furthermore less sensitive to mois-
ture stress than growth of the aerial parts of the vine. During flowering
and phase I of berry growth the highest possible soil moisture regime must
be maintained to insure maximum fruit set and cell division. Shoot growth
rate would have dropped by then while trunk growth will benefit from a high
soil moisture content in November. Though well developed trunks are not a
sought after characteristic of the vine at present, its value as a storage
organ may still be under-estimated. During phase II of berry growth, irri-
gation can be reduced to curb shoot growth further while the growth of ber-
ries are not very sensitive to moisture stress. Continued irrigations at
limited quantities during the ripening period will ensure increased sugar
contents, a low malate and TTA concentration without decreasing the yield.

It is therefore clear that optimum growth, grape yield and grape quality can be obtained by integration of controlled irrigation and phenological stage in a natural harmonious manner.

LITERATURE CITED

AGENBACH, W.A., 1977.   A study of must nitrogen content in relation to incomplete fermentations, yeast production and fermentation activity. Proc. S. Afr. Soc. Enol. Vitic., 66-88.

ALEXANDER, D. Mc E., 1964. The effect of high temperature regimes and short periods of water stress on development of small fruity sultana vines. Aust. J. Agric. Res. 16, 817-823.

ALLEWELDT, H., 1977. Growth and ripening of the grape berry. Proc. Int. Symp. on the Quality of the Vintage pp. 129-142. Cape Town, South Africa.

AMERINE, M.A., BERG, H.W. & CRUESS, W.V., 1972. Technology of Wine Making (Third Edition).   Avi Publishing Company Inc., Westport, Connecticut.

ANON, 1976. Ultra violet method for the determination of L-malic acid in foodstuffs. Boehringer GmbH, Mannheim.

BLACK, J.D.F., 1976. Trickle irrigation - A review. Part one. Hort. Abstr. 46, 69-74.

BLAKE, G.R., 1965. Bulk density. In : C.A. Black, D.D. Evans, J.L. White, L.E. Ensminger, F.E. Clark (eds). Methods of soil analysis. Agron. Series 9, Part 1, 374-390.

BöHM, W., 1979. Methods of Studying Root Systems. Springer-Verlag, Berlin, Heidelberg and New York.

BRANAS, J., 1967. L'irrigation dans le Midi de la France. Progr. Agric. Vitic. 167, 587-597. (Abstr.: Hort. Abstr. 38, 185, 196).

BRANAS, J., 1974. Viticulture. Imprimerie Déhan, Montpellier.

CHALMERS, D.J., MITCHELL, P.D. & VAN HEEK, L., 1981. Control of peach tree growth and productivity by regulated water supply, tree density and summer pruning. J. Amer. Soc. Hort. Sci. 106, 307-312.

CONRADIE, W.J., 1980. Seasonal uptake of nutrients by Chenin blanc in sand culture : I. Nitrogen. S. Afr. J. Enol. Vitic. 1, 59-65.

CONRADIE, W.J., 1981. Nutrient consumption by Chenin blanc grown in sand culture and seasonal changes in the chemical composition of leaf blades and petioles. S. Afr. J. Enol. Vitic. 2, 15-18.

COOMBE, B.G., 1976. The development of fleshy fruits. Ann. Rev. Plant. Physiol. 27, 207-228.

DENMEAD, O.T. & SHAW, R.N., 1962. Availability of soil water to plants as affected by soil moisture content and meteorological conditions. Agron. J., 54, 385-390.

DU PLESSIS, C.S., 1977. Grape components in relation to white wine quality. Proc. Int. Symp. on the Quality of the Vintage pp. 117-128. Cape Town, South Africa.

DUPONT, T.J. & MORLAT, R., 1980. Aspects geopedologiques da vignoble de Chinon et problems agroviticoles associes. Cann. Vigne. Vin. 14 (1), 1-18.

FREEMAN, B.M., 1978. Irrigated wines may be good but not great. The Australian Grapegrower and Winemaker 176, 11 & 16.

FREEMAN, B.M., & SMART, R.E., 1975. A root observation laboratory for studies with grapevines. <u>Am. J. Enol. Vitic.</u> 27, 36-39.

FREGONI, M., 1977. Effects of soil and water on the quality of the harvest. Proc. Int. Symp. on the Quality of the Vintage pp. 117-128. Cape Town, South Africa.

GATES, C.E. & BILBRO, J.D., 1978. Illustration of a cluster analysis method for mean separation. <u>Agron J.</u> 70, 462-465.

GOLDBERG, D. & SHMUELI, M., 1971. Drip irrigation - a method used under arid and desert conditions of high water and soil salinity. <u>South African Citrus Journal.</u> 448, 9-15.

HARDIE, W.J., 1981. pH and acidity regulation in the vineyard by water supply. Proceedings of a seminar on "Grape Quality : Assessment from vineyard to juice preparation". pp. 7-18. Melbourne, Australia.

HARDIE, W.J. & CONSIDINE, J.A., 1976. Response of grapes to water -deficit stress in particular stages of development. <u>Am. J. Enol. Vitic.</u> 27, 55-61.

HIDALGO, L., 1977. Methods of cultivation : The influence on the quality of the vintage. Proc. Int. Symp. on the Quality of the Vintage. pp. 277-289.

HOFäCKER, W., 1976. Untersuchungen über den Einfluss wechselnder Boden- feuchte auf Frunchtbarkeit, Beerenwachstum, Ertrag und Mostgewicht bei Reben. <u>Die Wein-Wiss.</u> 31, 1-8.

HOFäCKER, W., 1977. Untersuchungen zur Stoffproduktion der Rebe under dem Einfluss wechselnder Bodenwasserversorgung. *Vitis* 16, 162-173.

HOFäCKER, W., ALLEWELDT, G. & KHADER, S., 1976. Einfluss von Umweltfaktoren auf Beerenwachstum und Mostqualität bei der Rebe. *Vitis* 15, 96-112.

KASIMATIS, A.N., 1967. Grapes. In : Irrigation of Agricultural lands. (Eds. R.M. Hagan, H.R. Haise & T.W. Edminster). Agron. Series 11. 719-739. Am. Soc. Agron., Madison, Wisconsin.

KLIEWER, W.M. & ANTCLIFF, A.J., 1970. Influence of defoliation, leaf darkening and cluster shading on the growth and composition of Sultana grapes. *Am. J. Enol. Vitic.* 21, 26-36.

KLIEWER, W.M. & SCHULZ, H.B., 1964. Influence of environment on metabolism of organic acids and carbohydrates in Vitis vinifera. II Light. *Am. J. Enol. Vitic.* 15, 119-129.

LOMBARDO, V., 1972. Studies on the water balance in vines under semi- and mediterranean conditions. Rivista di Viticoltura e di Enologia 25, 3-17. (Abstr.: *Hort. Abstr.* 42, 5702, 1972).

McCARTHY, M.G., CIRAMI, R.M. & McCLOUD, P., 1983. Vine and fruit responses to supplementary irrigation and canopy management. *S. Afr. J. Enol. Vitic.* 4, 67-76.

NIJAR, C.S. & RANDHWANA, N.S., 1968. Effect of irrigation levels at different growth stages on cropping and quality of Arab-e-Shahi grapes. J. Res. Ludhiana 5, 178-391. (Abstr.: *Hort. Abstr.* 39, 6461, 1969).

PEACOCK, W.L., ROLSTON, D.E., ALJIBURY, F.K. & RAUSCHKOLB, R.S., 1977. Evaluating drip, flood and sprinkler irrigation of wine grapes. Am. J. Enol. Vitic. 28, 193-195.

REBELEIN, H., 1973. Rapid quantitative determination of tartaric acid. Chemie Mikrobiologie Technologie der Lebensmittel 2, 33-38.

RUTTEN, P., 1977. Besoins en eau la vigne. Place des equipments hydraliques dans un programme de restructuration du vignoble francais mediterranéen. Bulletin Technique D'Information. No. 319-320, 261-272.

SAAYMAN, D., 1981. Wingerdvoeding. In : J.D. Burger & J. Deist (eds). Wingerdbou in Suid-Afrika, V.O.R.I., Private Bag X5026, 7600 Stellenbosch, South Africa, pp. 343-383.

SAFRAN, B., 1977. Effects of cultivation on the quality of the vintage in hot regions. Proc. Int. Symp. on the Quality of the Vintage. pp. 243-262. Cape Town, South Africa.

SMART, R.E., 1974. Aspects of water relations of the grapevine (Vitis vinifera). Am. J. Enol. Vitic. 25, 84-91.

SMART, R.E. COOMBE, B.G., 1983. Water relations of grapevines. In : T.T. Kozlowski (ed). Water deficits and plant-growth VII, Academic Press, New York, pp. 137-196.

SMART, R.E. TURKINGTON, C.R. & EVANS, J.C., 1974. Grapevine response to furrow and trickle irrigation. Am. J. Enol. Vitic. 25, 62 - 66.

SNEDECOR, G.W. & COCHRAN, W.G., 1967. Statistical methods (sixth edition). The Iowa State University Press, Iowa, USA.

SOIL SURVEY STAFF, 1975. Soil taxonomy : A basic system for soil classifi-
        cation for making and interpreting soil surveys. Agric. Handbook
        No. 436, Soil Conservation Services, USDA.

SOMERS, T.C., 1977. A connection between potassium levels in the harvest on
        relative quality in Australian red wines. Proc. Int. Symp. on the
        Quality of the Vintage, 14-21 Feb. 1977, Cape Town, 142-148.

TATARENKO, R.K., 1971. Irrigation in vineyards. Vinodelie i. Vinogradar-
        stvo. S.S.S.R. 31 (8), 36-37. (Abstr.: Hort. Abstr. 42, 3400,
        1972).

TROMP, A., 1984. The effect of yeast strain, grape solids, nitrogen and
        temperature on fermentation rate and wine quality. S. Afr. J. Enol.
        Vitic. 5, 1 - 6.

TROMP, A. & CONRADIE, W.J., 1979. An effective scoring system for the sen-
        sory evaluation of experimental wines. Am. J. Enol. Vitic. 30,
        278-384.

TURNER, N.C. & KRAMER, P.J., 1980. Adaptation of plants to water and high-
        temperature stress. John Wiley & Sons., New York.

UNTERSTENHöFER, G., 1963. The basic principles of crop protection in field
        trials. Höfchen Br. Bayer Pflschutz.- Nachr. 16, 81-164.

VAADIA, Y. & KASIMATIS, A.N., 1961. Vineyard irrigation trials. Am. J.
        Enol. Vitic. 12, 88-98.

VAN ROOYEN, F.C., WEBER, H.W. & LEVIN, I., 1980. The response of grapes to
        a manipulation of the soil-plant-atmosphere continuum. I. Growth,
        yield and quality responses. Agrochemophysica 12, 59-68.

VAN DER WESTHUIZEN, J.H., 1980.   The effect of black plastic mulch on growth, production and root development of Chenin blanc vines under dryland conditions. S. Afr. J. Enol. Vitic. 1, 1 - 6.

VAN ZYL, J.L., 1981. Waterbehoeftes en Besproeiing. In : J.D. Burger & J. Deist (eds). Wingerdbou in Suid-Afrika. VORI, Private Bag X5026, 7600 Stellenbosch, South Africa, pp. 234-282.

VAN ZYL, J.L. & KENNEDY, C.S., 1983. Vine response to water stress induced by polyethylene glycol. S. Afr. J. Enol. Vitic. 4, 1-5.

VAN ZYL, J.L. & WEBER, H.W., 1977. Irrigation of Chenin blanc in the Stellenbosch area within the framework of the climate-soil-water-plant continuum. Proc. Int. Symp. on the Quality of the Vintage. pp. 331-350. Cape Town, South Africa.

VOS, P.J.A., ZEEMAN, W. & HEYMANN, H., 1978. The effect on wine quality of di-ammonium phosphate additions to musts. Proc. S. Afr. Soc. Enol. Vitic. 87-104.

WINKLER, A.J., COOK, J.A., KLIEWER, W.M. & LIDER, L.A., 1974. General Viti-culture. Univ. Calif. Press, Berkeley.

ZEEMAN, A.S., 1981. Oplei. In : J.D. Burger & J. Deist (eds). Wingerdbou in Suid-Afrika. VORI, Private Bag X5026, 7600 Stellenbosch, South Africa, pp. 185-201.

Table 1 :   Particulars of irrigation treatments applied in a trial with wine grapes.

Treatment	Soil moisture regime (%) during various phenological stages					Irrigation system
	Bud burst–flowering *1	Flowering* Phase I *2 of berry growth	Phase II of berry growth	Versaison – Harvesting	Post-harvest *3	
T1	25	25	25	25	+	Micro-jets
T2	50	50	50	50	+	"
T3	70	70	70	70	+	"
T4	90	90	90	90	+	"
T5	25	70	70	70	+	"
T6	70	25	70	70	+	"
T7	70	70	25	70	+	"
T8	70	70	70	25	+	"
T9*4	70	70	70	70	–	"
T10	90	90	90	90	+	Tricklers
T11	50	50	50	50	+	Sprinklers
T12	50	50	50	50	+	Flood

*1   All treatment plots received an irrigation before bud burst.

*2   Berry growth was divided into 3 phases (Winkler, et al., 1974)

*3   Treatments included either one (+) or no (–) water applications between harvesting and end of leaf-fall.

*4   T9 was ineffective in most years due to untimely rains

Table 2: Mean particle size analysis of plots in the various replicates of an irrigation trial.

Repli-cate	Clay (%) (< 0,002 mm)*				Silt (%) (0,02 - 0,002 mm)				Fine Sand (%) (0,2 - 0,02 mm)				Medium Sand (%) (0,05 - 0,2 mm)				Coarse Sand (%) (2,0 - 0,5 mm)			
	Depth (cm)				Depth (cm)				Depth (cm)				Depth (cm)				Depth (cm)			
	0-25	25-50	50-75	75-90	0-25	25-50	50-75	75-100	0-25	25-50	50-75	75-100	0-25	25-50	50-75	75-100	0-25	25-50	50-75	75-10
R1	16,81	17,51	17,45	20,66	8,68	9,02	8,97	7,64	58,25	57,32	56,70	54,30	11,20	10,55	11,17	11,45	3,61	3,45	3,92	3,7
R2	16,44	16,75	16,60	15,51	7,27	7,51	7,64	8,74	61,90	61,46	60,55	59,69	11,42	10,73	10,41	11,37	3,12	3,09	3,50	4,15
R3	15,73	19,30	17,73	16,20	7,59	8,46	10,49	13,49	61,05	56,0	56,64	52,24	12,51	12,83	13,31	12,78	2,75	2,51	2,82	3,4
R4	21,14	21,86	20,14	14,51	10,62	12,49	13,40	16,67	51,76	50,59	48,77	49,49	12,07	10,32	12,12	13,17	2,80	2,24	3,49	4,04
R5	21,36	21,41	18,51	17,63	13,48	12,64	14,40	14,05	51,29	50,40	46,09	49,49	11,85	11,47	12,16	13,71	2,31	2,17	2,56	3,4
R6	24,45	21,32	15,65	14,18	11,94	13,00	13,81	11,59	48,06	48,67	49,09	52,53	11,88	12,28	11,84	14,38	2,50	2,68	3,65	3,8
R 1-3	16,33	17,85	17,26	17,46	7,85	8,33	9,03	9,96	60,40	58,26	57,30	55,41	11,71	11,37	11,63	11,87	3,16	3,02	3,41	3,7
R 4-6	22,32	21,70	18,10	15,44	12,01	12,01	13,87	14,10	50,37	49,89	47,98	50,50	11,93	11,36	12,04	13,75	2,54	2,36	3,23	3,7

*Fraction size

Table 3. Results of a chemical soil analysis in the experimental vineyard

Depth (m)	pH (0,1 M KCl)	Resistance* (Ω)	Bray No. 2		Extractable Cations (m.e. kg^{-1}) 1 M NH4 Cl)			
			P (mg kg^{-1})	K (mg kg^{-1})	K	Na	Ca	Mg
			Replicates 1 – 3					
0 – 25	6,75	833	26,5	225,3	5,98	2,73	47,30	50,12
26 – 50	6,98	835	20,5	148,3	4,09	2,95	64,45	53,33
50 – 75	7,09	640	22,3	140,8	4,19	3,69	125,40	69,67
75 – 100	7,18	690	22,0	113,3	4,40	4,35	116,15	92,83
			Relicates 4 – 6					
0 – 0,25	7,66	549	35,8	305,3	7,87	3,74	126,95	52,08
25 – 0,50	7,93	425	27,0	288,7	8,20	6,35	169,25	61,67
50 – 0,75	7,89	333	17,3	272,8	7,87	10,04	176,20	74,25
75 – 1,00	8,04	297	12,0	235,8	8,15	11,91	215,60	90,50

* – Measured on the saturation paste in a standard USDA soil cup.

TABLE 4. Grape yield (kg/vine) of Colombar/99R during the period 1977/78-1982/83

Treatment	1977/78	1978/79	1979/80	1980/81	1981/82	1982/83	Cumulative 77/78 – 82/83
T1	8,342 A	12,158 B	14,78 B	11,33 A	15,77 A	15,18 A	77,57 A
T2	8,050 A	13,810 A	17,86 A	14,08 A	16,28 A	20,23 A	90,37 A
T3	8,274 A	13,156 B	18,29 A	15,28 A	18,30 A	23,23 A	97,07 A
T4	8,270 A	13,238 B	19,04 A^	14,74 A	17,57 A	20,62 A	93,48 A
T5	8,688 A1	15,166 A1	18,46 A	15,22 A	19,12 A	23,23 A	100,77 A ¥
T6	9,134 A	12,348 B	15,19 B	12,93 A	14,34 A	20,54 A	84,49 A
T7	7,634 A	12,986 B	14,89 B	15,06 A	16,99 A	19,89 A	87,46 A
T8	7,298 A	12,632 B	15,18 B	14,17 A	14,22 A	18,22 A	82,21 A
T9	8,652 A⊔	12,954 B	16,68 B	16,85 A1	20,35 A1	25,131A	101,97 A ¥
T10	7,946 A	11,746 B	16,47 B	15,31 A	17,65 A	19,70 A	88,83 A
T11	8,068 A	14,750 A	18,96 A	15,36 A	17,75 A	20,57 A	95,46 A
T12	8,388 A	14,080 A	17,82 A	15,41 A	16,67 A	19,62 A	91,99 A
Mean	8,229	13,252	16,97	14,69	17,13	20,52	90,97
c.v. (%)	15,0	10,6	12,2	15,5	18,70	24,55	13,4
D-Value (P≤0,05)	n.S.	3,07	4,53	N.S.	N.S.	N.S.	N.S.

N.S.   = Not Significant

c.v.   = coefficient of variance

D-Value = Newman-Keuls test

A, B   = Grouping according to the Scott-Knott test

Table 5:   ANOVA for the orthogonal test of planned contrasts performed on cumulative grape yield data.

Source	Degrees of Freedom	Mean Squares	F-value	Probability Level
Blocks	4	503,142704	3,413	0,016
Treatments	11	271,506694	1,842	0,075
(T1–T4) vs. Rest	1	54,61	0,370	0,25
(T5–T9) vs. (T10–T12)	1	4,73	0,032	0,25
T2 vs. T1 T3 + T4	1	3,73	0,025	0,25
T1 vs. T3 + T4	1	1044,9	7,089	0,015
T3 vs. T4	1	32,22	0,219	0,25
T7 vs. T5, T6, T8 + T9	1	96,04	0,652	0,25
T5 + T9 vs. T6 + T8	1	1623,60	11,015	0,005
T5 vs. T9	1	3,60	0,024	0,25
T6 vs. T8	1	13,00	0,088	0,25
T10 vs. T11 + T12	1	80,20	0,544	0,25
T11 vs T12	1	30,10	0,204	0,25
Error	44	147,401		

TABLE 6. Pruning mass of Colombar/99R during the period 1977/78 - 1982/83

Treatment	Pruning Mass (kg/vine)						
	1977/78	1978/79	1979/80	1980/81	1981/82	1982/83	77/78 - 82/83
T1	1,79 A	1,32 A	1,49 A	1,35 A	1,26 A	0,77 A	7,992 A
T2	1,82 A	2,09 B	2,22 B	1,74 A	1,56 A	1,07 B	10,506 B
T3	2,18 B	2,01 B	2,18 B	2,13 B	1,94 A	1,21 B	11,650 B
T4	2,44 B	2,14 B	2,35 B	2,14 B	1,79 A	1,06 B	11,936 B
T5	2,04 A	1,88 B	2,58 B	2,30 B	2,08 A	1,21 B	12,096 B
T6	2,37 B	2,01 B	2,15 B	2,05 A	1,94 A	1,11 B	11,638 B
T7	1,85 A	1,92 B	1,59 A	1,80 A	1,86 A	1,12 B	10,154 A
T8	1,75 A	1,78 B	1,90 A	1,67 A	1,67 A	1,17 B	9,948 A
T9	2,23 B	2,20 B	2,26 B	2,31 B	2,25 A	1,42 C	12,684 B
T10	1,63 A	1,46 A	1,56 A	1,62 A	1,47 A	0,89 A	8,644 A
T11	2,31 B	2,23 B	2,20 B	1,81 A	1,89 A	1,09 B	11,538 B
T12	2,01 A	2,09 B	2,14 B	1,75 A	1,72 A	2,04 B	10,770 B
Mean	2,04	1,93	2,06	1,89	1,79	1,10	10,796
c.v. (%)	18,9	18,8	19,8	21,8	22,5	28,4	16,53
D-Value (P ≤ 0,05)	0,84	0,70	0,89	0,90	0,88	0,68	3,899

c.v. = coefficient of variance

D-Value = Newman-Keuls test

A, B = Grouping according to the Scott Knott test

TABLE 7. Average grape yield/pruning mass ratio for Colombar/99R during the period 1977/78 - 1982/83

Treatment	Yield/Pruning Mass Ratio
T1	9,80 A
T2	8,73 B
T3	8,36 B
T4	8,08 B
T5	8,49 B
T6	7,30 B
T7	8,82 B
T8	8,90 B
T9	8,16 B
T10	10,61 A
T11	8,33 B
T12	8,87 B
Mean	8,71
c.v. (%)	10,73
D-Value (P $\leqslant$ 0,05)	2,04

c.v.   = coefficient of variance

D-Value = Newman-Keuls test

A, B   = Grouping according to the Scott-Knott test

TABLE 8. Concentration (% of dry mass) of mineral elements in leaf blades and petioles from plots maintained at four moisture regimes (T1 - T4) during 1978/79

| Elements | Leaf Blades | | | | | D-Value |
	T1	T2	T3	T4	Mean	$(P \leqslant 0,05)$
N	2,21	2,36	2,33	2,28	2,30	NS
P	0,17	0,18	0,18	0,18	0,18	NS
K	0,73	0,85	0,88	0,80	0,82	NS
Na	0,02	0,02	0,02	0,03	0,029	NS
Ca	1,40	1,49	1,65	1,65	1,55	NS
Mg	0,39	0,34	0,36	0,36	0,37	NS
	Petioles					
N	0,60	0,63	0,64	0,62	0,63	NS
P	0,21	0,30	0,30	0,28	0,28	NS
K	2,23	2,69	2,76	2,38	2,52	NS
Na	0,07 a	0,0 bab	0,05 b	0,05 b	0,061	$0,014^{**}$
Ca	1,02 a	1,16 ab	1,31 b	1,25 b	1,19	$0,22^{**}$
Mg	0,96 a	0,82 b	0,88 ab	0,83 b	0,88	$0,12^{**}$

NS   = Not Significant

**   = Highly Significant $(P \leqslant 0,01)$

a,b   = Figures not followed by the same letter(s), differ significantly at a 5% level

TABLE 9. Concentration (% of dry mass) of mineral elements in leaf blades
and petioles from plots maintained at four moisture regimes
(T1 - T4) during 1979/80

Element	Leaf Blades					D-Value (P ≤ 0,05)
	T1	T2	T3	T4	Mean	
N	2,43	2,30	2,31	2,33	2,34	NS
P	0,16	0,16	0,17	0,16	0,16	NS
K	0,82	0,86	0,86	0,84	0,85	NS
Na	0,02	0,02	0,02	0,02	0,02	NS
Ca	1,66	1,73	1,77	1,74	1,73	NS
Mg	0,43	0,39	0,38	0,39	0,40	NS
	Petioles					
N	0,63	0,65	0,64	0,64	0,65	NS
P	0,23	0,26	0,30	0,29	0,27	NS
K	2,74	2,88	2,90	2,74	2,82	NS
Na	0,09	0,08	0,06	0,09	0,085	NS
Ca	1,22	1,26	1,34	1,30	1,28	NS
Mg	1,17	1,00	0,98	1,05	1,05	NS

NS = Not Significant

TABLE 10. Concentration (% of dry mass) of mineral elements in leaf blades and petioles from plots maintained at four moisture regimes and irrigated by different irrigation systems during 1980/81

Elements	Leaf Blades								D-Value (P $\leq$ 0,05)
	T1	T2	T3	T4	T10	T11	T12	Mean	
N	2,19	2,19	2,25	2,29	2,20	2,27	2,29	2,24	NS
P	0,32	0,32	0,28	0,29	0,25	0,35	0,29	0,30	NS
K	0,85 a	0,90 a	0,93 ab	0,97 ab	0,94 ab	1,12 b	1,04 ab	0,97 ab	0,20**
Na	0,019 a	0,024 a	0,020 a	0,027 a	0,022 a	0,049 b	0,023 a	0,026 a	0,015*
Ca	1,61	1,57	1,61	1,80	1,77	1,60	1,67	1,67	NS
Mg	0,37	0,34	0,32	0,36	0,33	0,32	0,36	0,34	NS
	Petioles								
N	0,73	0,75	0,79	0,77	0,70	0,74	0,73	0,74	NS
P	0,52	0,49	0,50	0,49	0,42	0,55	0,47	0,50	NS
K	2,52 a	2,08 bc	2,04 bc	2,25 ab	1,81 c	2,10 bc	1,83 c	2,09 bc	0,40**
Na	0,050 ab	0,037 a	0,038 a	0,049 ab	0,042 ab	0,059 b	0,037 a	0,045 ab	0,021*
Ca	1,50	1,45	1,61	1,68	1,62	1,47	1,50	1,55	NS
Mg	0,85	0,72	0,72	0,78	0,84	0,70	0,88	0,79	NS

NS   = Not Significant

*   = Significant at a 5% level

**   = Significant at a 1% level

a,b   = Figures not followed by the same letter(s), differ significantly at a 5% level.

TABLE 11   Significance of differences among treatments with regard to berry size and composition (1979/80)

Berry Fresh Mass (g)	Berry Volume (cm³)	T SS (°B)	TTA (g dm⁻³)	pH	Tartrate (g dm⁻³)	Malate (g dm⁻³)	Tartrate/ Malate ratio
T10 a	T10 a	T10 a	T4 a	T6 a	T1 a	T4 a	T1 a
T4 a	T4 a	T1 a	T2 a	T1 a	T6 a	T2 a	T10 b
T2 a	T2 a	T8 b	T3 ab	T8 a	T3 b	T3 a	T6 c
T8 a	T8 a	T2 b	T6 b	T2 a	T2 b	T8 a	T8 c
T3 a	T3 a	T3 b	T8 b	T3 a	T8 b	T6 a	T3 c
T6 b	T6 b	T4 b	T1 c	T4 a	T10 b	T1 b	T2 c
T1 c	T1 c	T6 b	T10 c	T10 a	T4 b	T10 b	T4 c

T10, T4 = Treatments decrease in value from top to bottom

a, b   = Means followed by the same letter or combination of letters do not differ significantly at a 5% level using the Newman-Keuls test

TABLE 12. Means of data obtained over a six year period (1977/78 – 1982/83) for must analyses of Colombar grapes under different irrigation treatments

Total Soluble Solids		Total Titratable Acidity		Sugar/Acid Ratio		pH-Values	
Treatment ranking	°B	Treatment ranking	g dm^{-3}	Treatment ranking	Ratio	Treatment ranking	Values
T8	18,46	T4	9,76 a	T8	2,07 a	T8	3,33 a
T10	18,37 ab	T9	9,75 a	T10	2,04 ab	T9	3,31 a
T1	18,34 abc	T11	9,74 a	T7	2,02 abc	T1	3,30 a
T7	18,17 abc	T3	9,73 a	T1	2,01 abcd	T5	3,30 a
T12	18,14 abc	T6	9,69 a	T12	1,93 bcde	T2	3,30 a
T5	17,89 abcd	T2	9,65 ab	T5	1,89 cde	T7	3,29 a
T4	17,90 bcd	T5	9,59 abc	T11	1,87 de	T3	3,29 a
T11	17,87 bcd	T12	9,54 abc	T2	1,87 de	T12	3,29 a
T9	17,85 bcd	T7	9,10 bc	T3	1,87 de	T6	3,29 a
T12	17,81 cd	T10	9,09 bc	T4	1,86 e	T4	3,28 a
T3	17,80 cd	T1	9,04 bc	T9	1,85 e	T11	3,28 a
T6	17,40 d	T8	9,03 c	T6	1,83 e	T10	3,27 a

a, b = Figures followed by the same letter or combination of letters do not differ significantly at a 5% level using the Newman-Keuls test

} Grouping according to the Scott-Knott test

TABLE 13. Means of data obtained over a six year period (1977/78 – 1982/83) for must analyses of Chenin blanc grapes under different irrigation regimes

Treatment	Total Soluble Solids (°B)	Total Titratable Acidity (g dm^{-3})	Sugar/Acid Ratio
T1	19,48 a ⎫	7,33 a ⎫	2,65 a ⎫
T2	19,88 a ⎭	7,88 a ⎭	2,52 a ⎭
T3	18,98 ab ⎫	8,70 a ⎫	2,18 ab ⎫
T4	18,87 b ⎭	10,15 b ⎭	1,86 b ⎭

a,b = Means followed by the same letter or combination of letters do not differ significantly at a 5% level using the Newman–Keuls test

⎫
⎭ = Grouping according to the Scott–Knott test

TABEL 14. Element concentration (mg dm^{-3}) in must from an irrigation trial on Colombar grapes during the 1979/80 season

Treatment	N	P	Na	Ca	Mg
T1	713 a	129 ab	12,2	51	104 a
T2	633 a	129 ab	11,3	52	91 bc
T3	598 ab	125 ab	10,2	68	92 bc
T4	653 a	130 ab	10,4	50	91 bc
T5	682 a	139 ab	9,8	51	91 bc
T6	705 a	154 a	11,2	57	101 ab
T7	653 a	134 ab	13,8	52	95 abc
T8	795 a	139 ab	13,5	60	105 a
T9	703 a	153 a	9,4	50	97 abc
T10	438 b	123 ab	8,6	53	92 bc
T11	523 ab	113 b	12,6	47	87 c
T12	620 ab	142 ab	10,1	53	99 ab
Mean	643	134	11,1	54	85
c.v. (%)	13,8	11,7	23,5	24,6	5,9
D-Value (P ≤ 0,05)	194**	34**	5,7*	NS	12,2**

N.S. = Not Significant

c.v. = coefficient of variance

*   = Significant (P ≤ 0,05)

**   = Highly Significant (P ≤ 0,01)

a, b = Figures not followed by the same letter(s) differ significantly at a 5% level

TABLE 15. Element concentration (mg dm^{-3}) in must from an irrigation trial on Colombar grapes during the 1981/82 season

Treatment	N	P	K	Na	Ca	Mg
T1	473	340 ab	1654 a	23	51	94
T2	501	269 ab	1766 ab	20	52	90
T3	529	304 ab	1711 ab	22	51	91
T4	533	258 a	1837 ab	23	51	96
T5	503	320 ab	1860 ab	23	53	91
T6	489	350 ab	1720 ab	22	54	101
T7	502	355 b	1766 ab	22	50	95
T8	490	335 ab	1710 ab	24	51	96
T9	509	346 ab	1936 b	22	52	93
T10	474	284 ab	1632 a	21	51	92
T11	497	342 ab	1741 ab	24	52	100
T12	536	310 ab	1704 ab	23	51	95
Mean	503	318	1753	22	52	94
c.v. (%)	13,0	25,4	11,1	18,9	12,7	12,1
D–Value (P$\leq$0,05)	NS	96**	232**	NS	NS	NS

NS   = Not Significant

c.v. = coefficient of variance

*   = Significant (P $\leqslant$ 0,05)

**   = Highly Significant (P $\leqslant$ 0,01)

a,b   = Figures not followed by the same letter(s) differ significantly at a 5% level.

TABLE 16. Element concentration $(mg\ dm^{-3})$ in must from an irrigation trial on Colombar grapes during the 1980/81 season

Treatment	P	K	Na	Ca	Mg
T1	138 ac	1206	18	45	107 a
T2	130 ab	1247	19	47	97 ab
T3	123 ab	1341	17	45	94 b
T4	115 ab	1236	16	43	96 bc
T5	110 b	1429	15	49	98 abc
T6	154 c	1465	15	52	105 ac
T7	113 b	1223	18	44	96 bc
T8	123 ab	1318	17	48	98 abc
T9	130 ab	1416	16	48	97 abc
T10	123 ab	1233	16	46	97 abc
T11	129 ab	1323	17	48	96 bc
T12	126 ab	1199	18	50	101 abc
Mean	126	1303	17	48	98
c.v. (%)	15,9	18,5	30,1	17,6	9,0
D–Value (P ⩽ 0,05)	24**	288**	NS	NS	11**

NS   = Not Significant

c.v. = coefficient of variance

*   = Significant (P ⩽ 0,05)

**   = Highly Significant (P ⩽ 0,01)

a,b = Figures not followed by the same letter(s) differ significantly at a 5% level

TABLE 17. Tasting panel scores (%) of experimental wines from Colombar grapes produced under various irrigation treatments

Treatment	Season				Mean
	1978/79	1979/80	1980/81	1981/82	1978/79-1981/82
T1	60,0	49,8	45,7	56,6	53,0
T2	44,1	50,0	40,0	55,6	47,4
T3	50,0	52,1	35,0	49,0	46,5
T4	52,9	49,3	36,5	56,6	48,8
T5	61,2	43,6	40,7	48,2	48,5
T6	52,9	50,7	37,9	59,1	50,2
T7*	69,4	-	42,1	55,2	55,6
T8	46,9	47,1	44,3	57,0	48,8
T9	56,9	42,8	42,8	58,3	50,2
T10	54,1	45,0	47,8	57,0	51,0
T11*	51,9	-	45,7	51,1	49,6
T12	60,6	52,1	37,1	58,0	52,0
D-Value (P ≤ 0,05)					NS

* = Treatments ignored in statistical analysis

NS = Not Significant

TABLE 18. Viticultural and enological data for three crop levels applied
to Colombar under different irrigation treatments

Crop load	Actual Yield (kg/vine)	Sugars (°B)	Total Titratable Acidity (g dm^{-3})	Fresh Mass of Bunches (g)	Fresh Mass per 100 berries (g)	Wine Quality * (%)
100%	17,13 a	18,1 a	9,34 a	156,97 a	202,98 a	55,2 a
75%	11,93 b	18,2 a	9,26 a	262,89 a	203,93 a	51,6 a
50%	8,36 c	18,1 a	9,27 a	253,00 a	206,57 a	49,7 a

a,b = Means followed by the same letter do not differ significantly at
      a 5% level

*   = Tasting panel scores

TABLE 19. Effect of irrigation treatment on the incidence of <u>Botrytis</u> <u>cinerea</u> sour rot and total bunch rot of Chenin blanc at Robertson

Treatment	Botrytis Rot (%)		Sour rot (%)		Total Bunch Rot (%)	
	1978/79	1979/80	1978/79	1979/80	1978/79	1979/80
T1	9,0	27,1	12,1	13,3	18,8	33,9
T2	6,1	14,6	30,3	12,1	24,6	22,2
T3	9,6	24,3	24,5	24,1	30,8	35,8
T4	9,3	32,4	21,1	22,9	28,0	45,2
T6	24,2	20,7	27,3	19,1	44,3	32,5
T8	0,6	6,5	1,5	3,9	2,3	8,9
D-Value (P ≤ 0,05)	7,5	12,9	15,8	9,50	15,9	16,5

TABLE 20. Effect of irrigation treatment on the incidence of <u>Botrytis</u> <u>cinerea</u>, sour rot and total bunch rot of Colombar at Robertson

Treatment	Botrytis Rot (%)		Sour Rot (%)		Total Bunch Rot (%)			
	1978/79	1979/80	1978/79	1979/80	1978/79	1979/80	1980/81	1981/82
T1	4,60	7,31	10,05	10,44	13,70	15,43	17,32	2,52
T2	7,70	14,17	18,45	21,61	239,00	29,33	28,60	3,60
T3	7,75	17,35	25,20	21,15	29,90	31,45	37,64	3,44
T4	6,05	15,96	22,88	22,67	26,40	32,78	37,80	2,76
T6	5,30	9,17	23,10	13,43	26,50	18,95	29,20	3,36
T8	4,15	10,04	13,25	14,30	16,25	20,55	26,60	3,16
D-Value (P ≤ 0,05)	3,75	5,73	9,63	5,69	9,85	7,98	14,43	NS
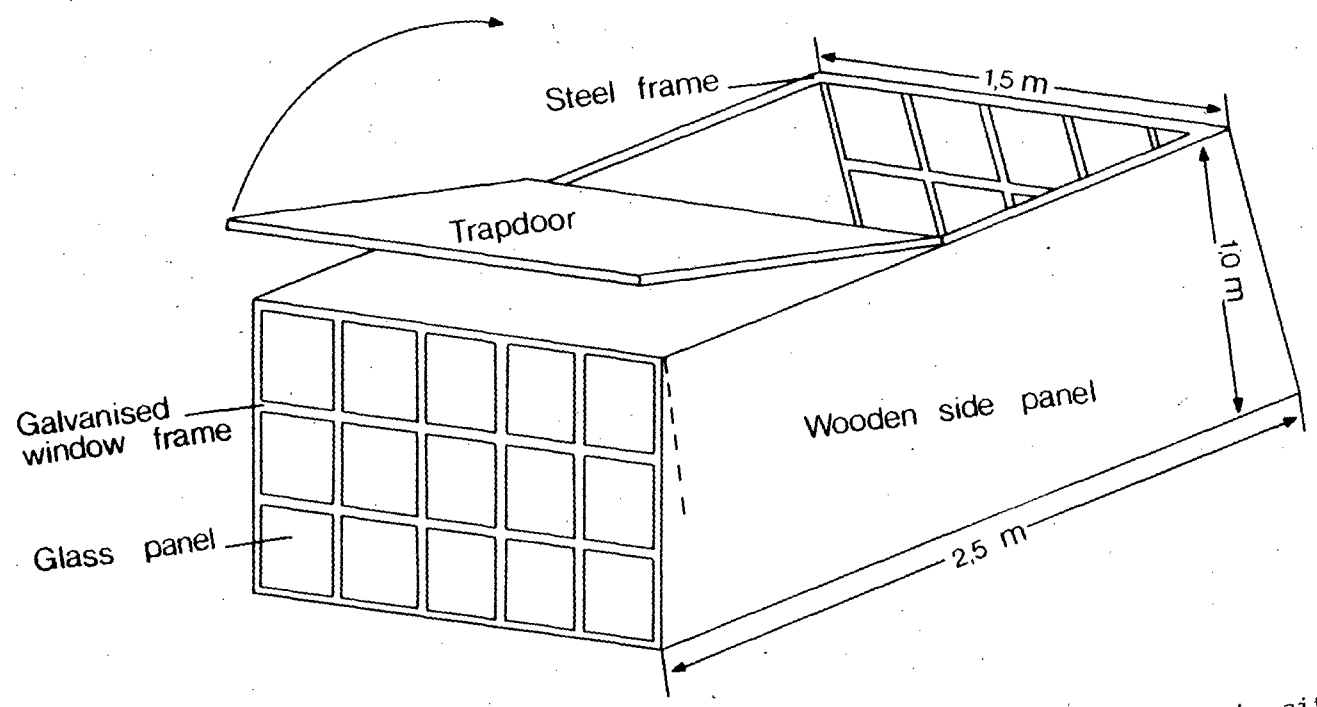
Fig. 1: Chamber with glass panels for studying root growth _in situ._
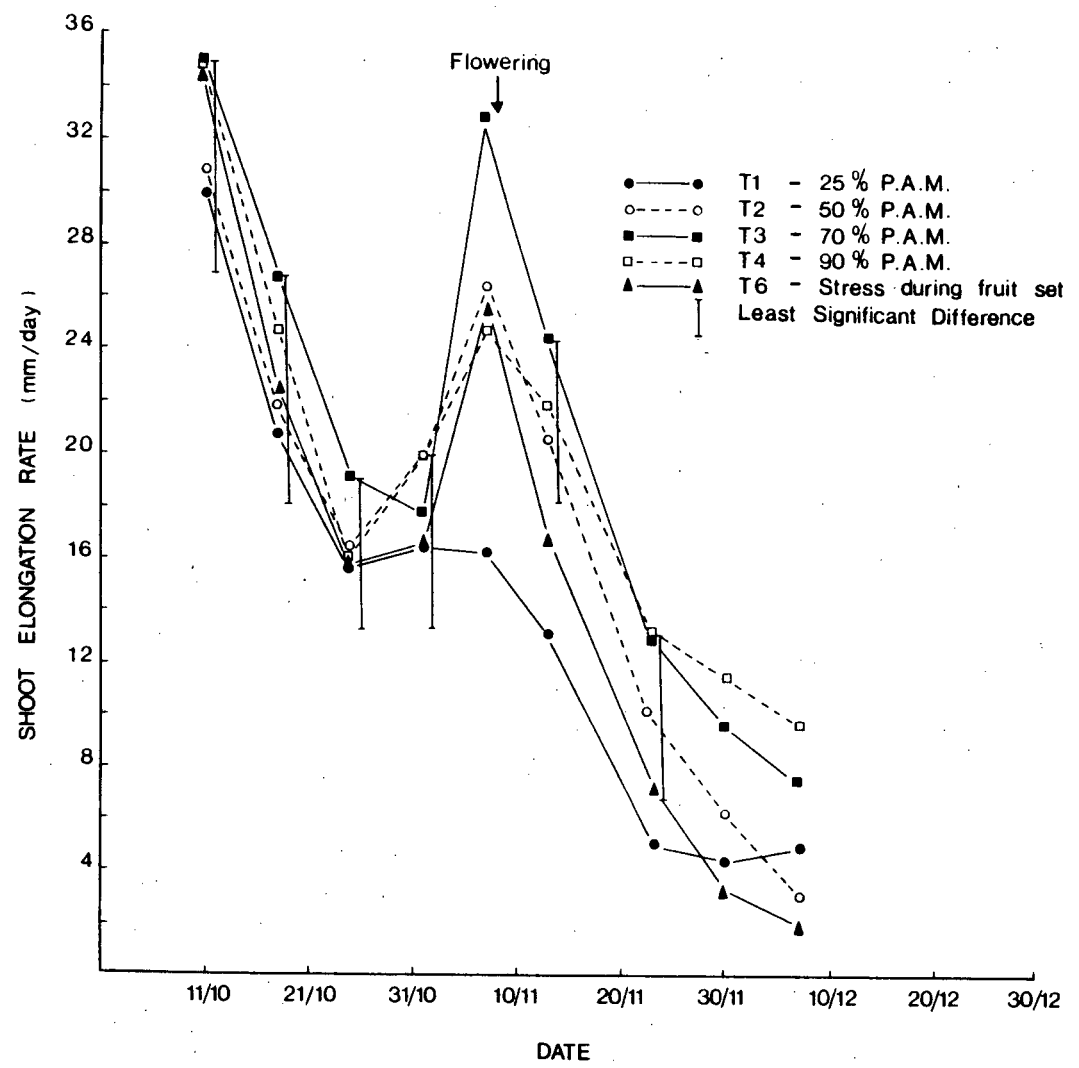
Fig. 2: Effect of irrigation treatments on shoot elongation rates of Colombar/99R in the 1979/80 season.
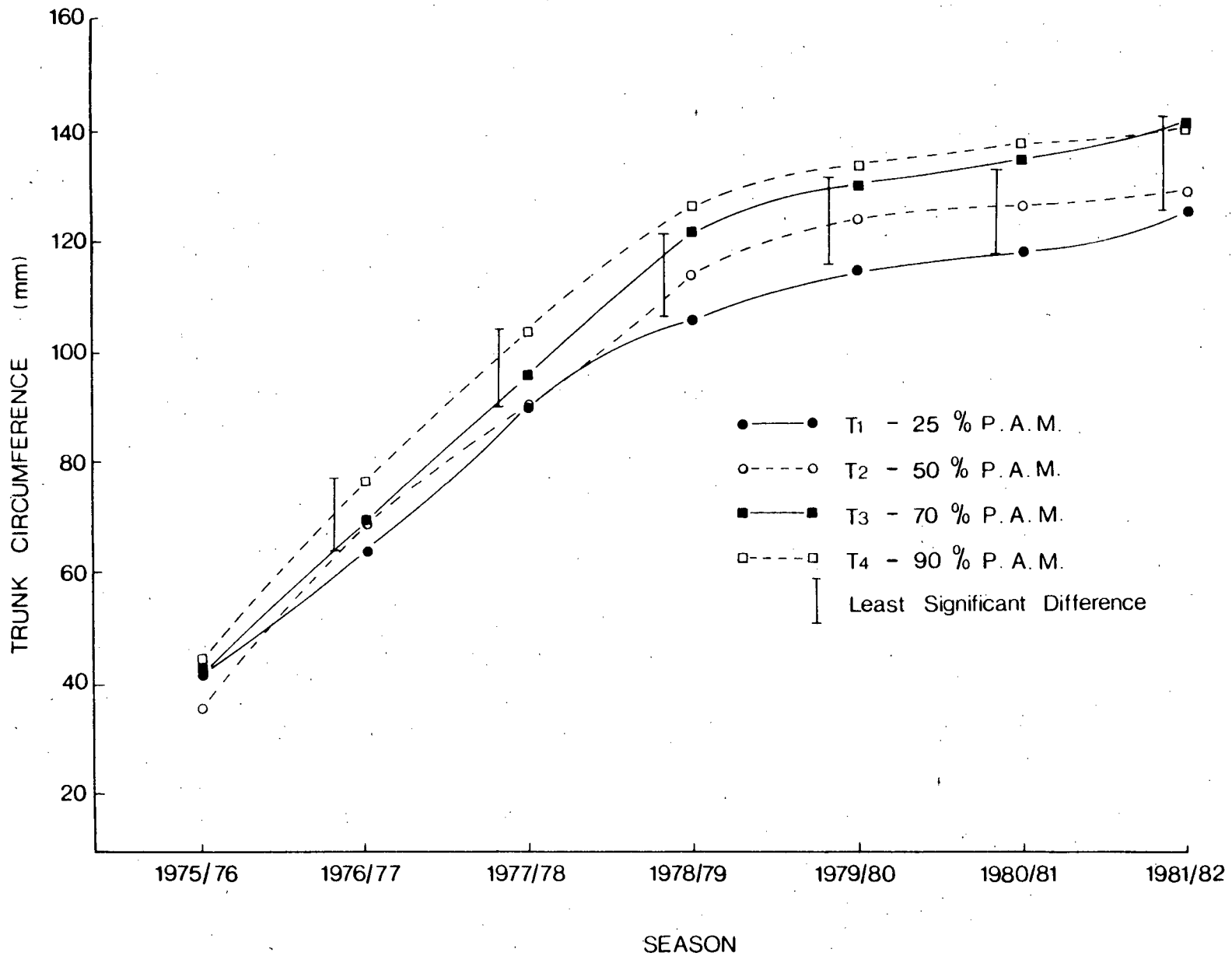
Fig. 3: Long term effect of irrigation treatments on trunk curcumference of Colombar/99R.
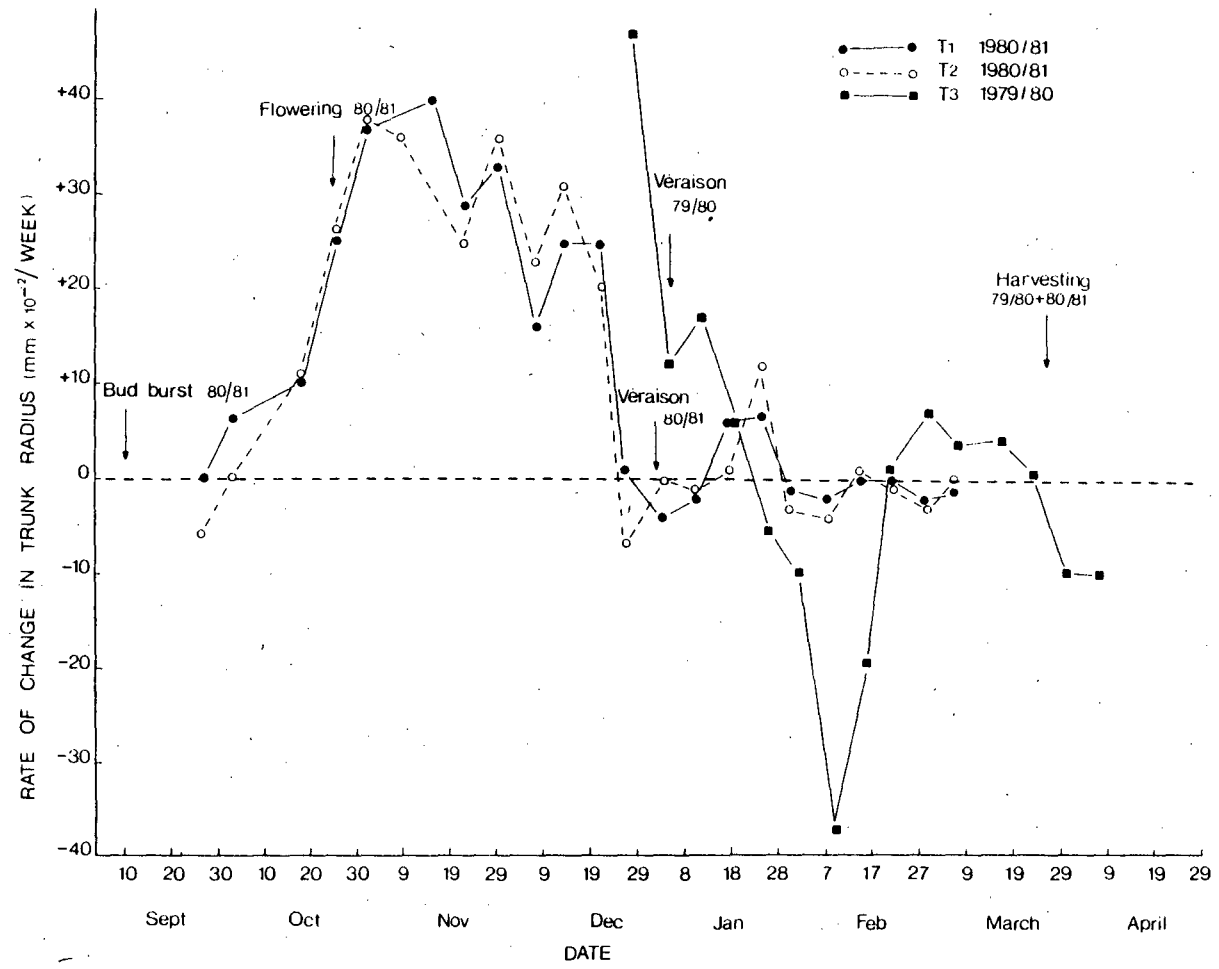
Fig. 4: Change in trunk radius due to phenological stage of Colombar/99R
in an irrigation trial at Robertson.
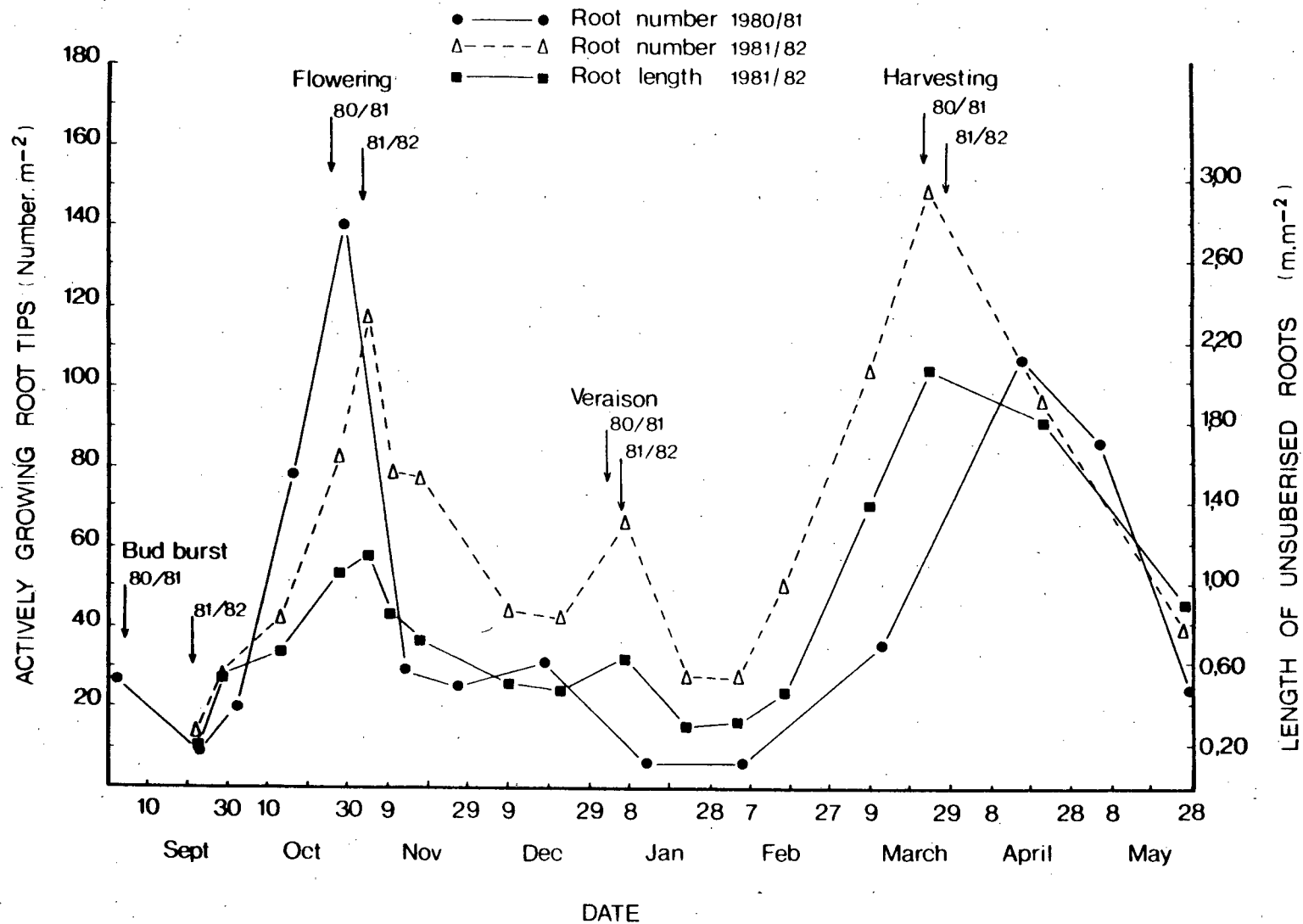
Fig. 5: Fluctuation in root formation in terms of root number and root length for Colombar/99R during the course of two seasons (means for all four treatments).
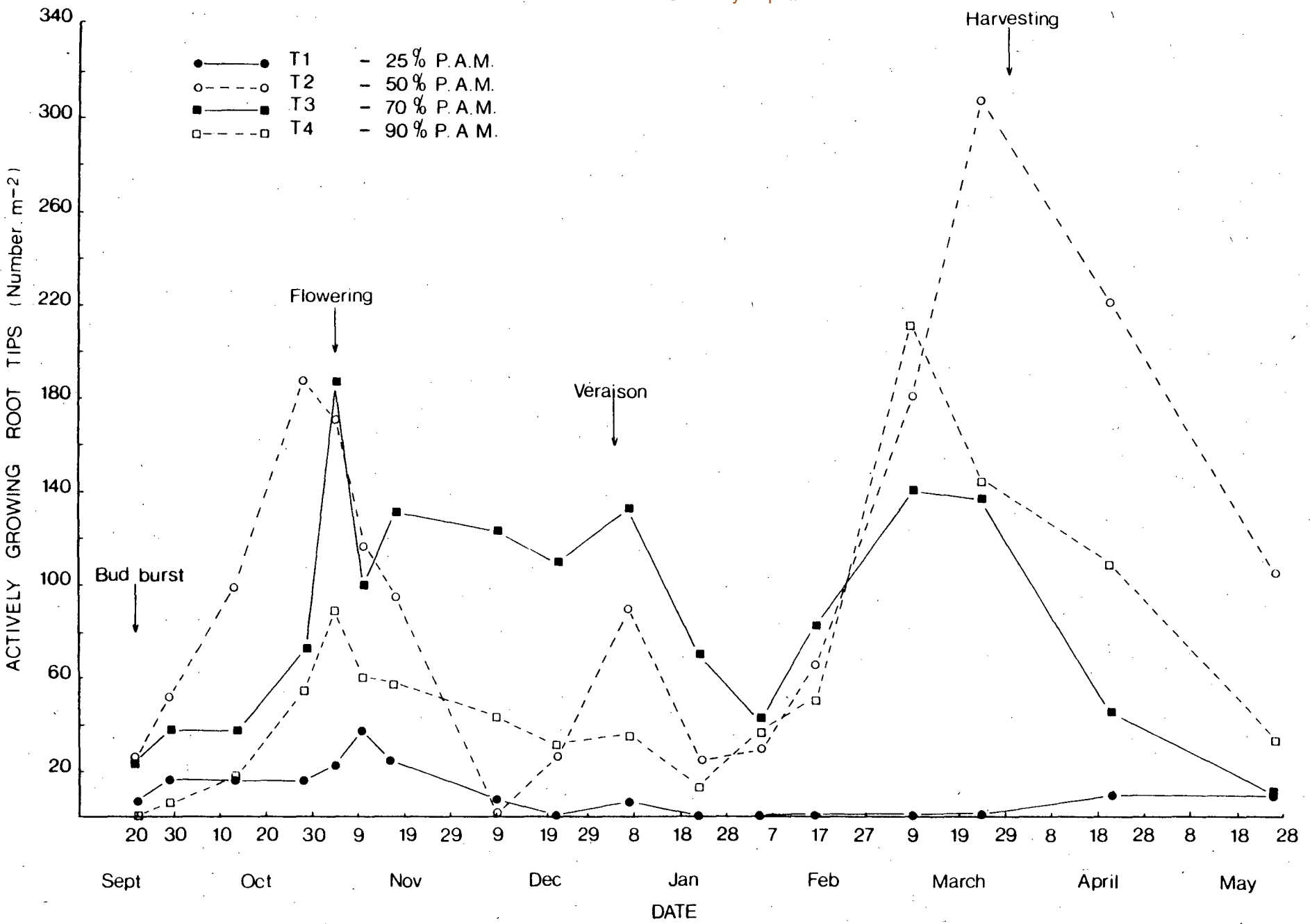
Fig. 6: Effect of irrigation treatments on root formation of Colombar/99R during the course of the 1981/82 season.
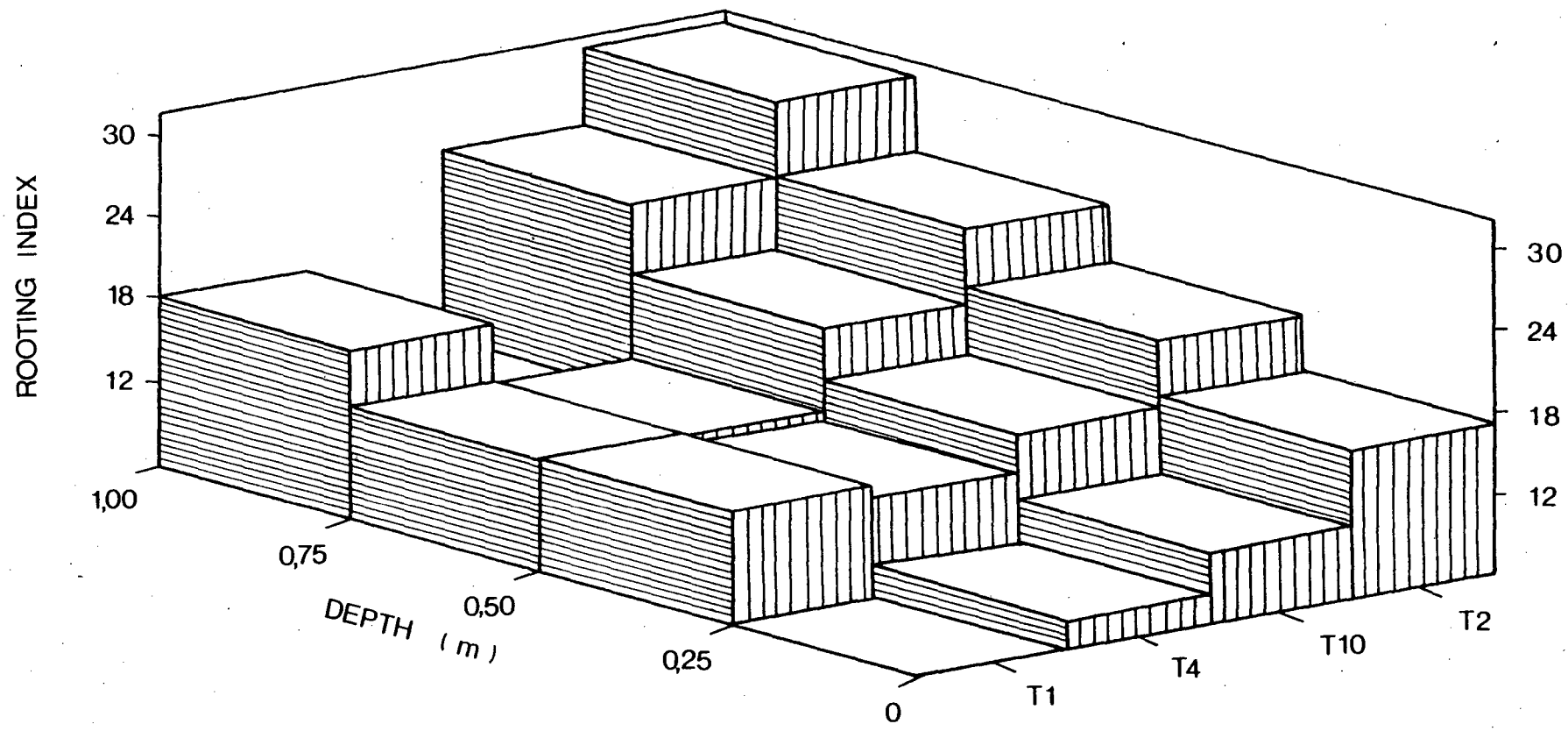
Fig. 7: Effect of four soil water regimes on the rooting index of Colombar/99R at different soil depths.
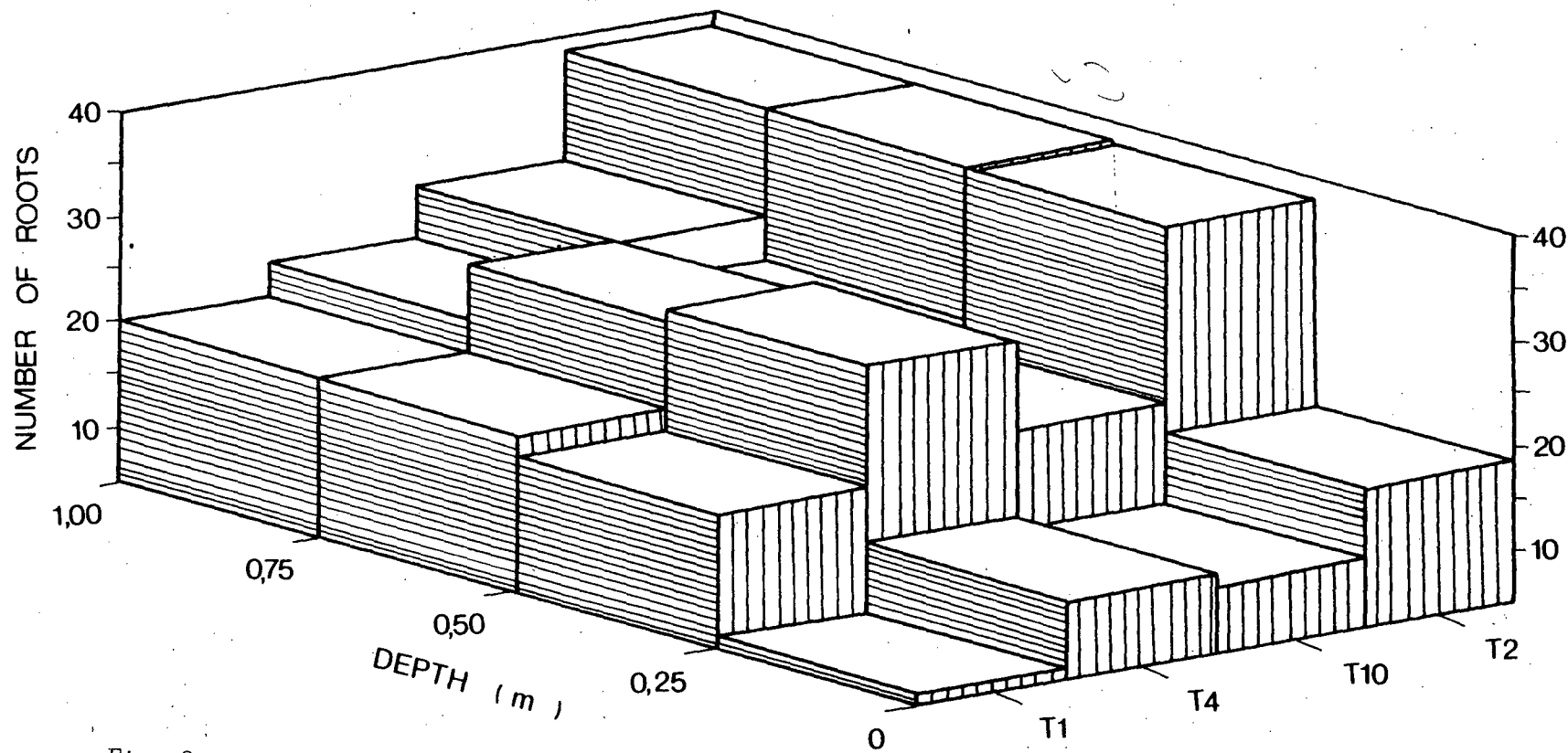
Fig. 8: Effect of four soil water regimes on the total number of roots of Colombar/99R at different depths.
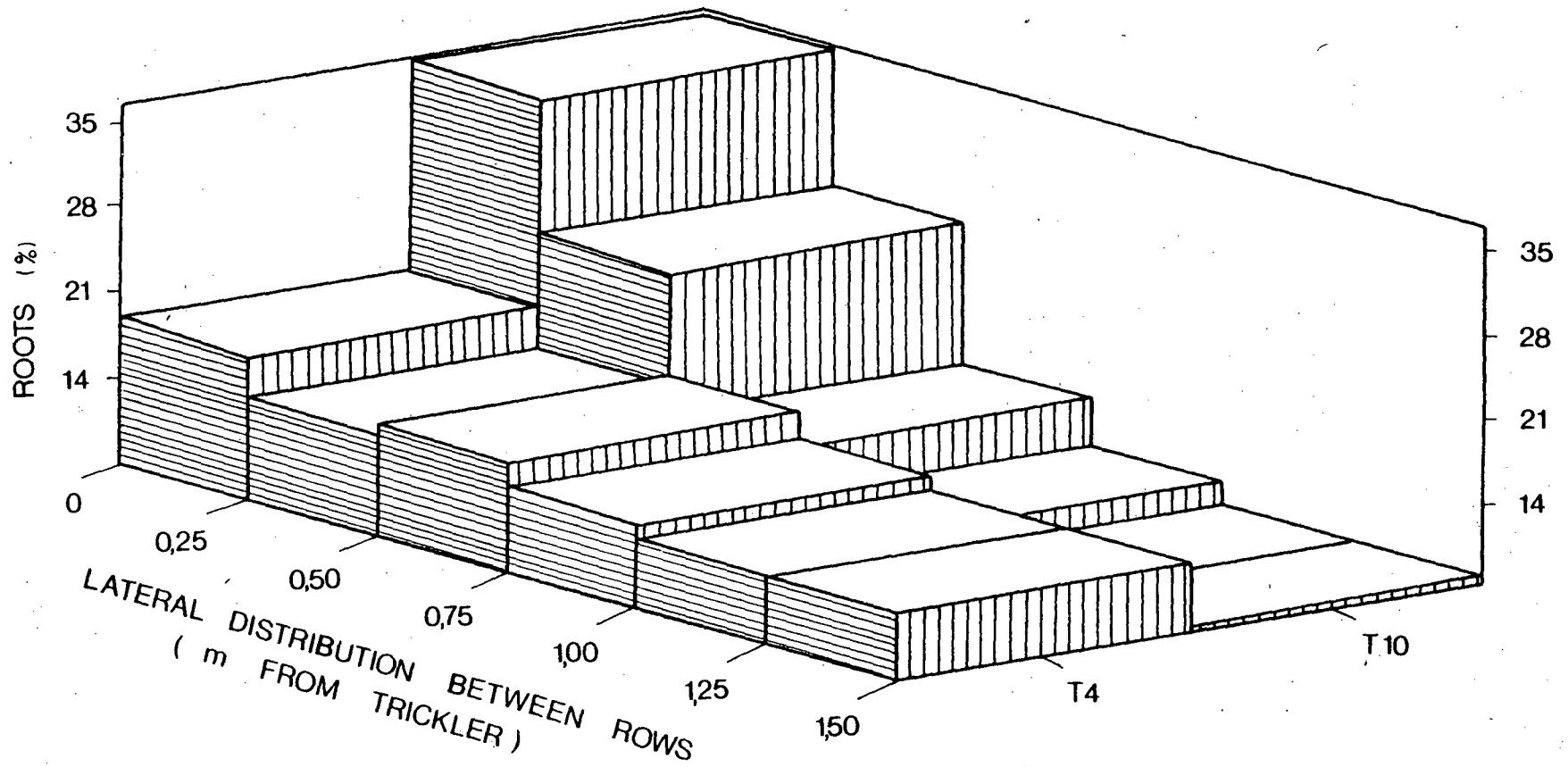
Fig. 9: Effect of micro-jets (T4) and tricklers (T10) on the root distribution of Colombar/99R
between rows as indicated by the percentage of roots.
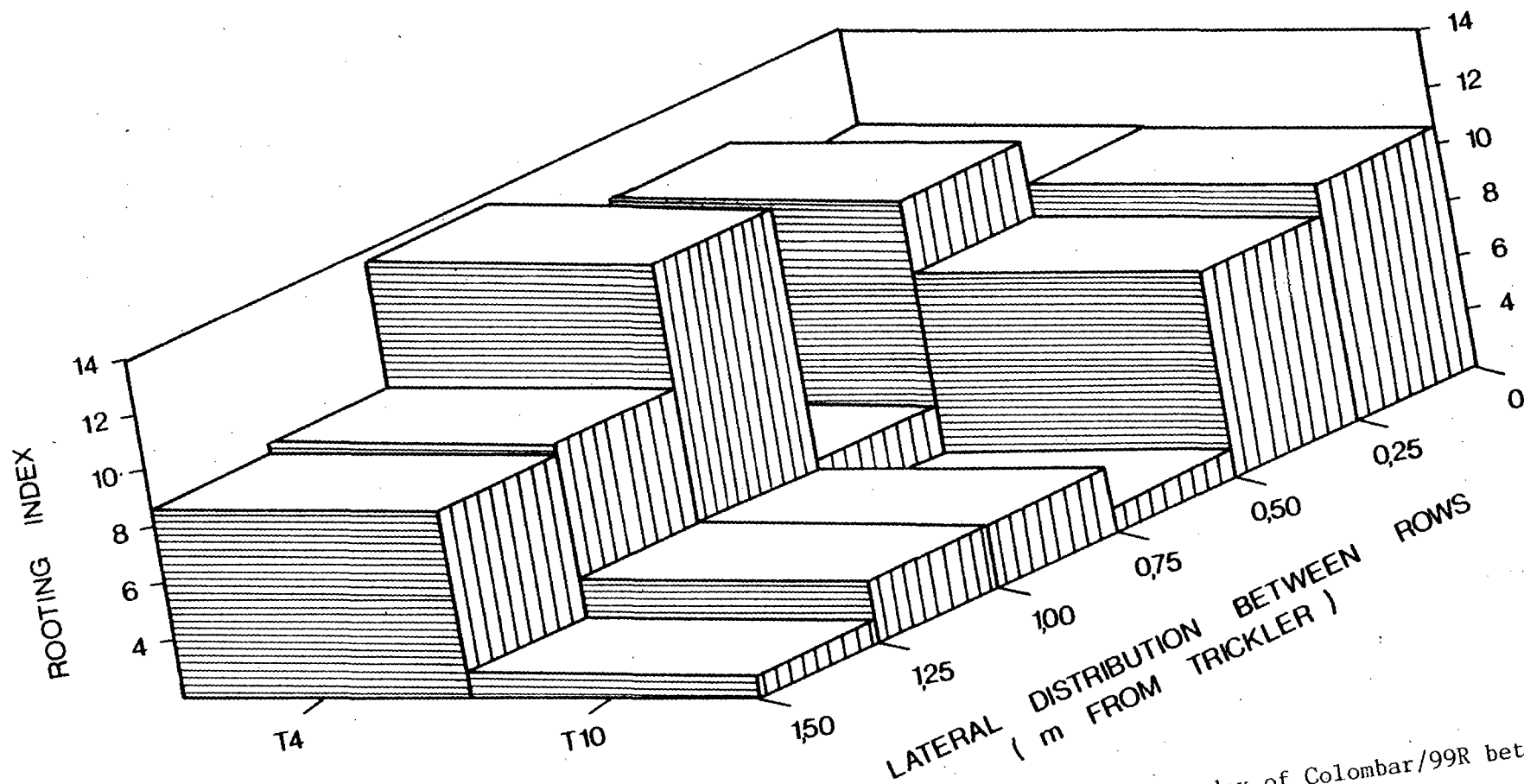
Fig. 10: Effect of micro-jets (T4) and tricklers (T10) on the rooting index of Colombar/99R between rows.
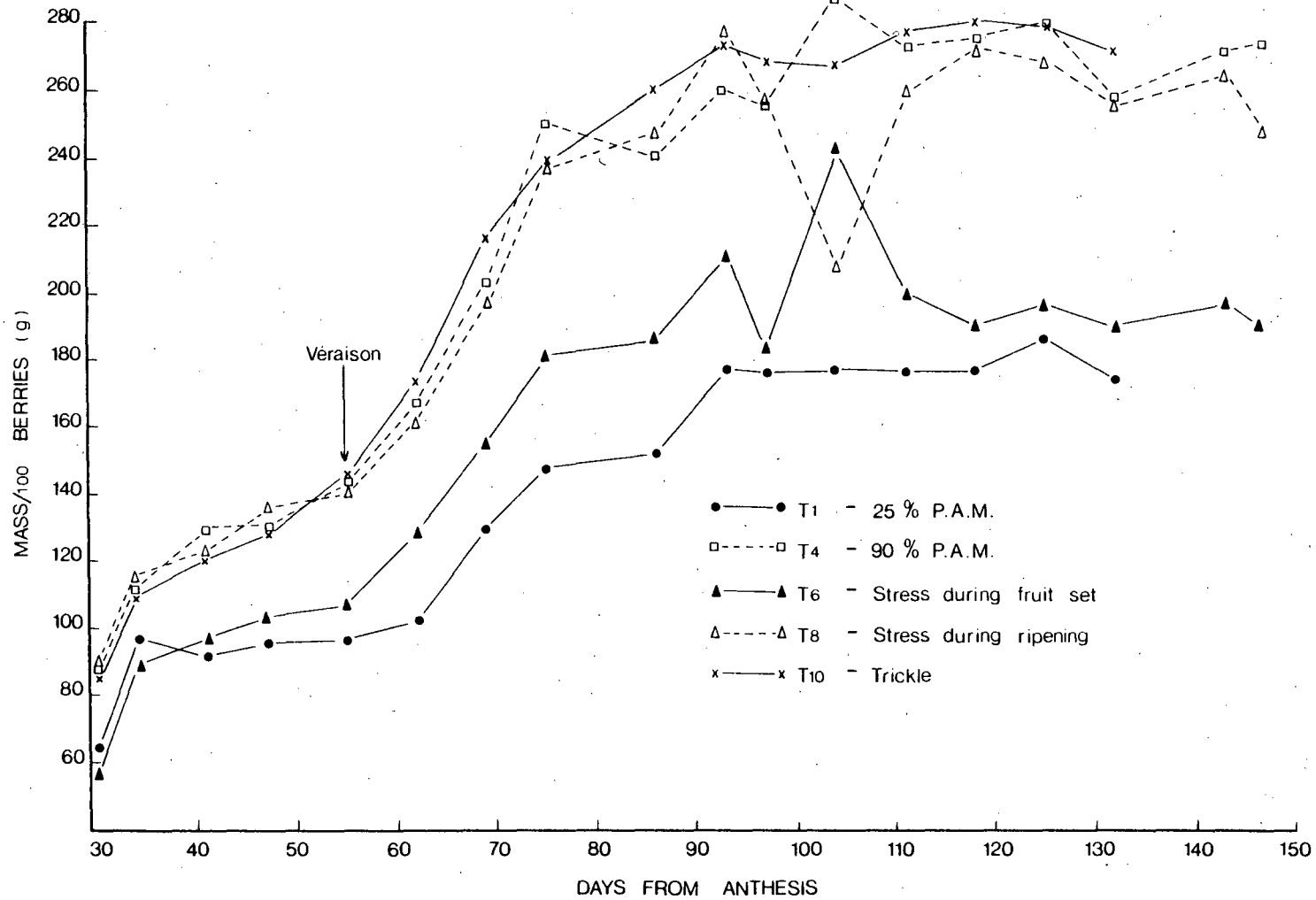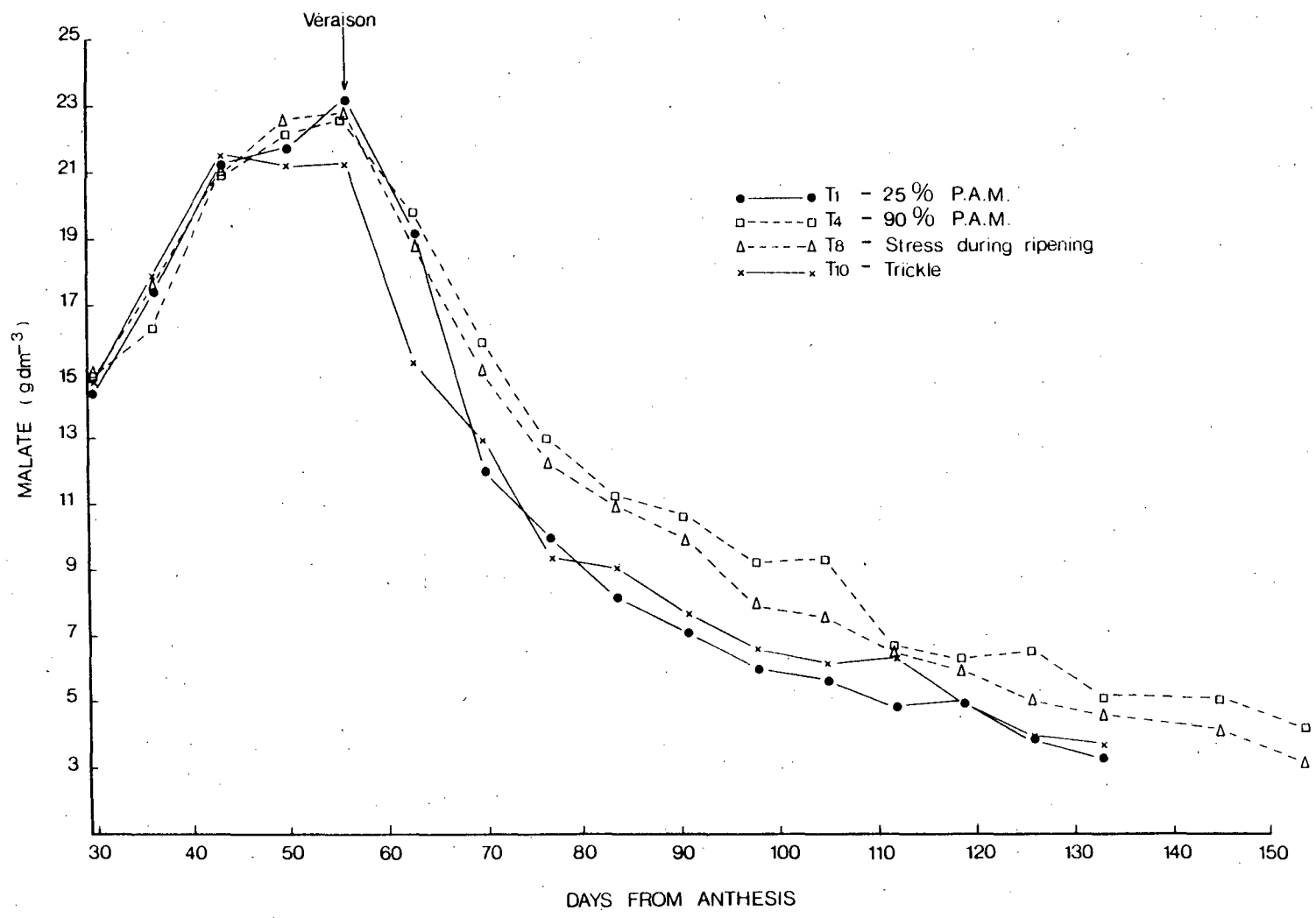
Fig. 11: Effect of irrigation treatments on cumulative berry mass of Colombar grapes during the 1979/80 season
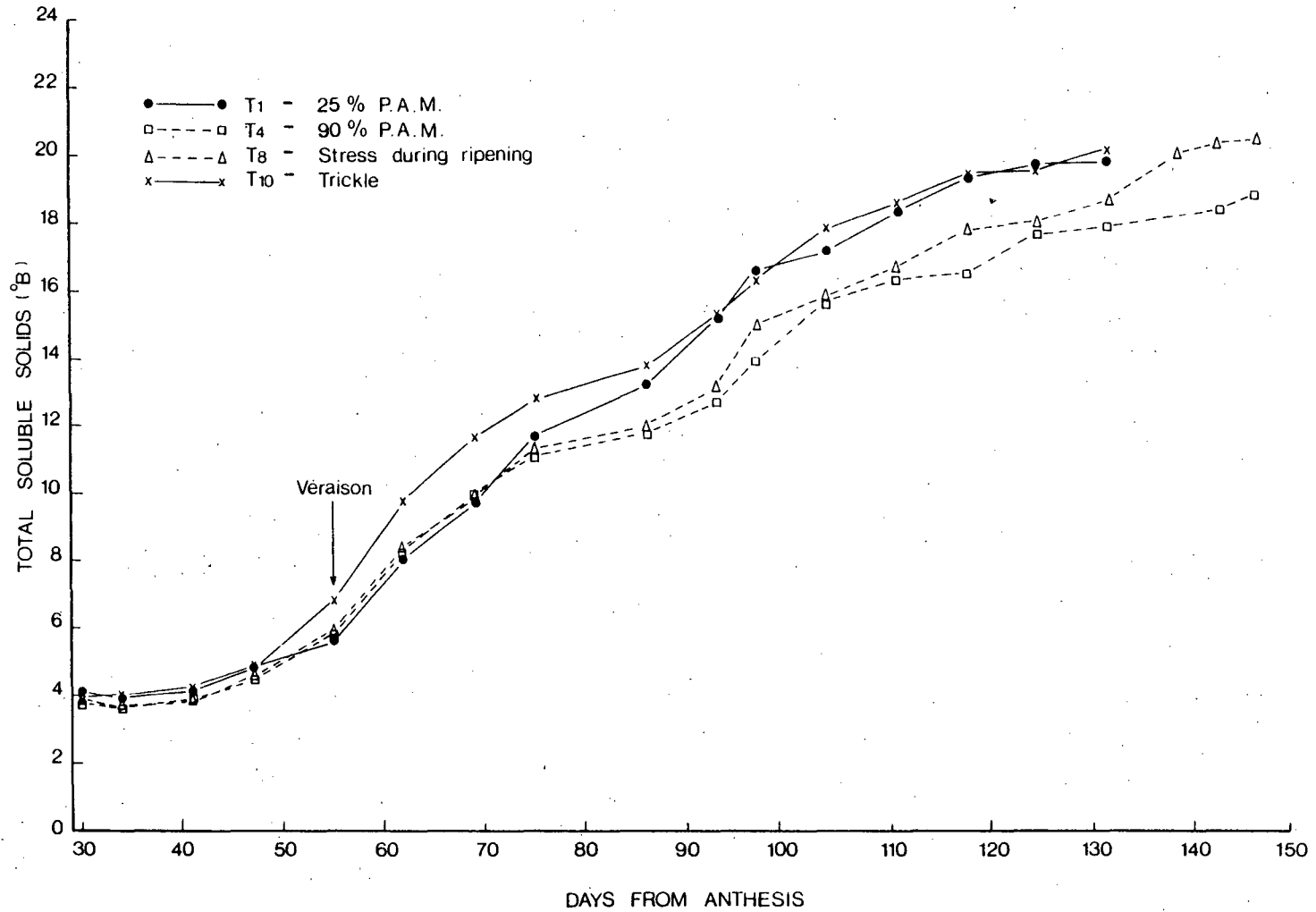
Fig. 12:   Effect of irrigation treatments on the increase of total soluble solids in
Colombar grapes during the 1979/80 season.
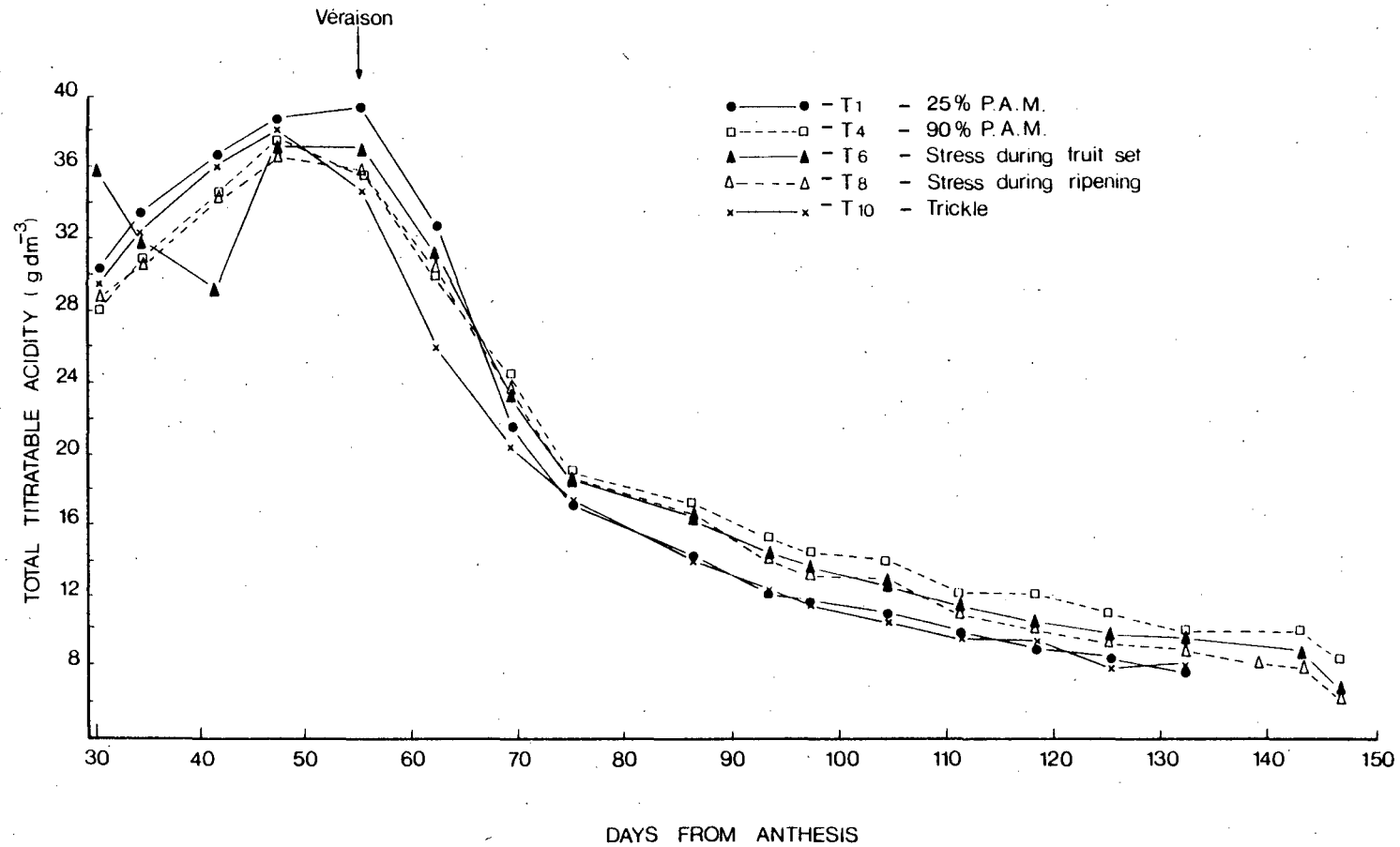
Fig 13: Effect of irrigation treatments on the total titratable acidity in Colombar grapes during the 1979/80 season.
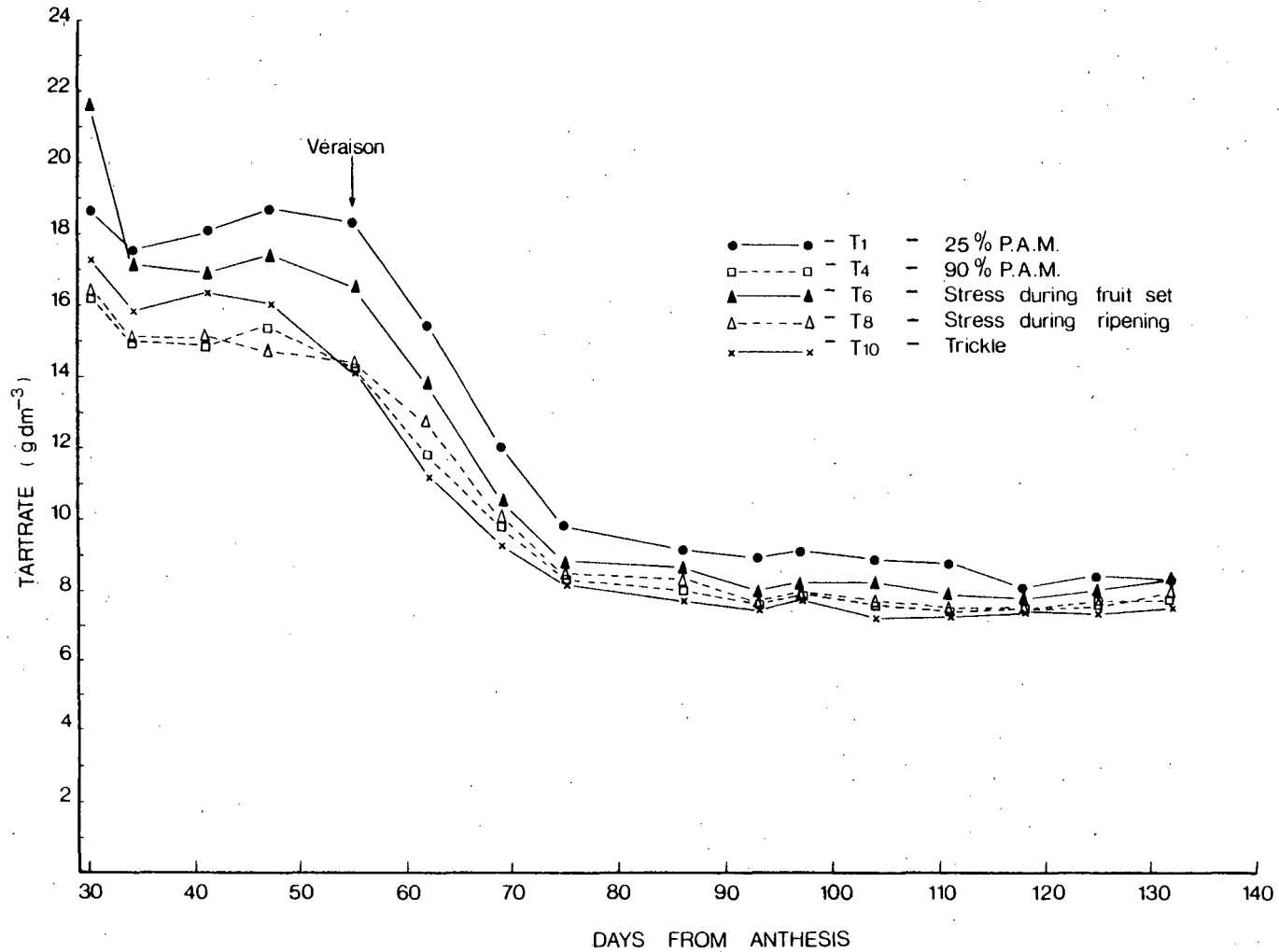
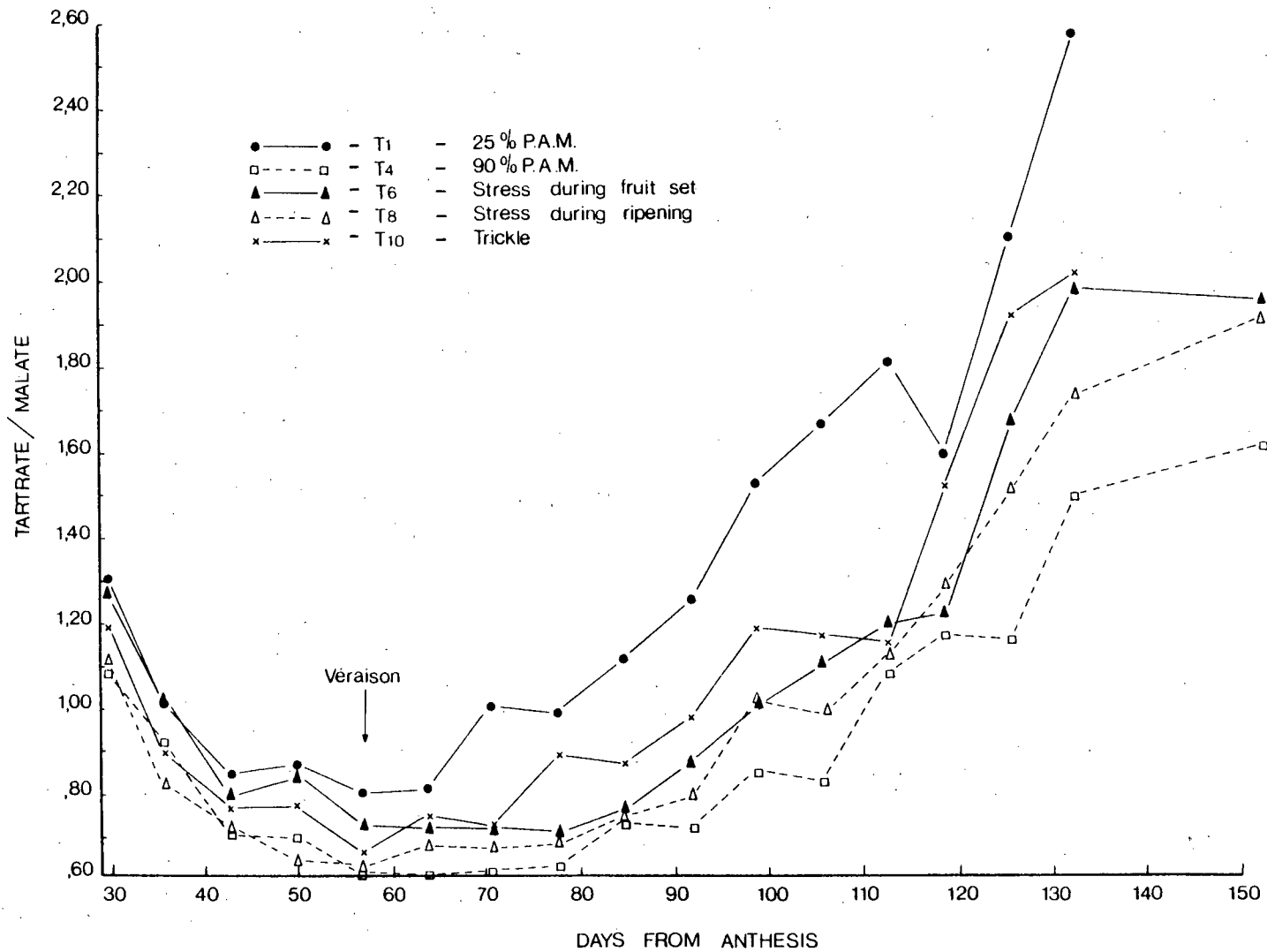Fig. 14:   Effect of irrigation treatments on tartrate concentration in Colombar grapes during the 1979/80 season.

Fig. 15: Effect of irrigation treatments on malate concentration in Colombar grapes during the 1979/80 season.

Fig. 16: Effect of irrigation treatments on tartrate/malate ratios in Colombar grapes during the 1979/80 season.
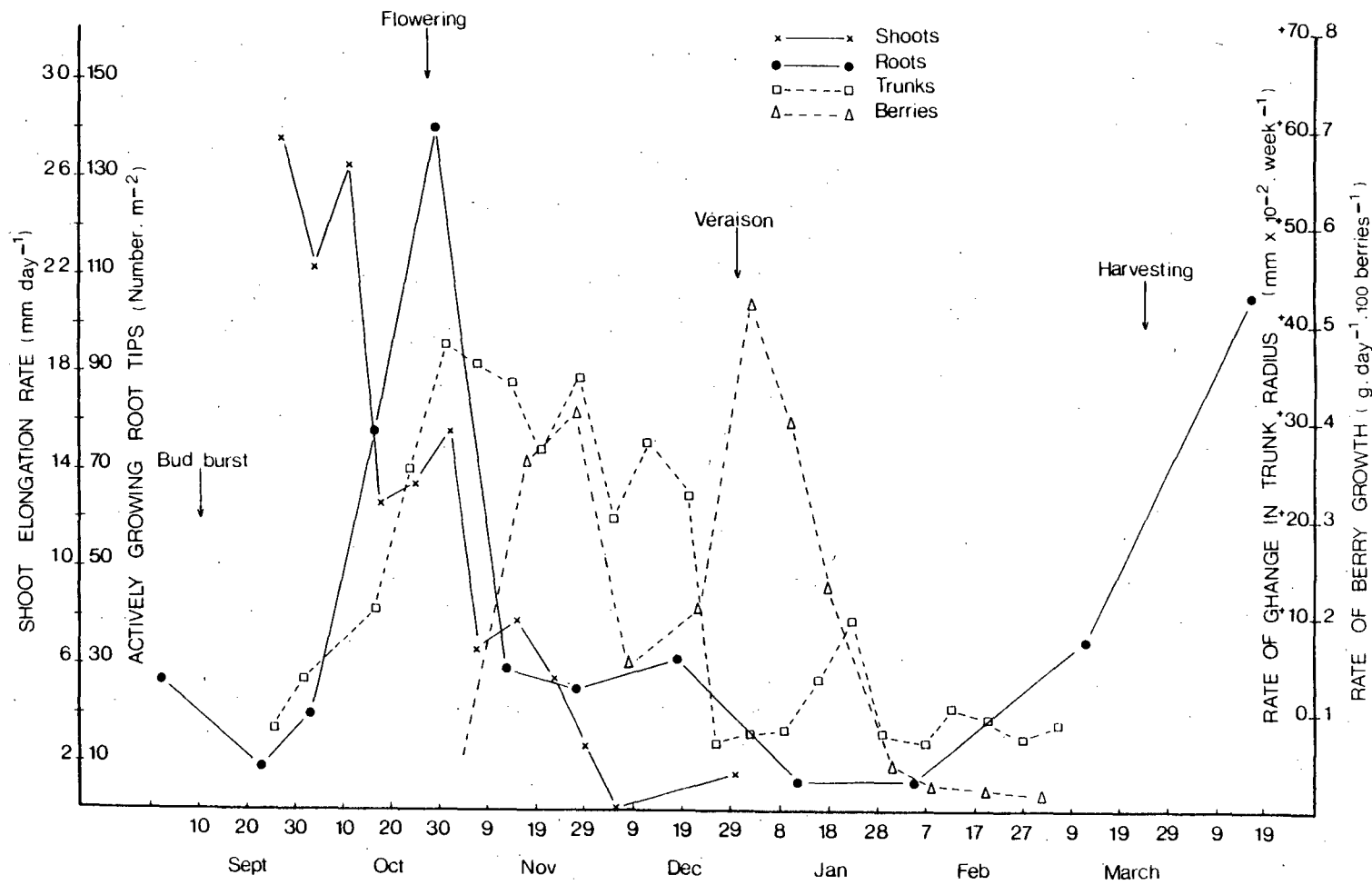
Fig. 17:   Interrelationship among the growth rates of various plant parts as determined in an irrigation trial with Colombar/99R at Robertson.

CHAPTER 5

CONSUMPTIVE WATER USE OF GRAPEVINES IN AN IRRIGATION TRIAL COMPRISING DIFFE-
RENT SOIL WATER REGIMES AND FOUR IRRIGATION SYSTEMS

INTRODUCTION

The scheduling of irrigation is at present based on the estimation of evapo-
transpiration or on the actual measurement of soil water status after such
relevant factors as the water holding capacity of the soil have been deter-
mined. Evapotranspiration of vineyards can be predicted using metereolo-
gical formulae or evaporimeters on condition that conversion factors, known
as crop factors, are available. These factors are determined empirically.
Although a highly significant correlation was found between evaporation mea-
sured with the United States Weather Bureau class A-pan, widely accepted as
the standard evaporimeter, and potential evapotranspiration as estimated by
Blaney & Criddle (1950), Turc (1953) and Thornthwaite (1954) using metereo-
logical data, the use of these formulae is questionable in the case of vines
and deciduous trees (Van der Westhuizen, 1964; Claassen, 1969; Du Pisani,
1970). The Penman equation (Penman, 1948) is the most accurate of the mete-
reological formulae, but requires the most climatic measurements. Du Pisani
(1970) found the highest correlation (r = 0,99) between potential evapo-
transpiration and Class A-pan evaporation in a comparative study which also
included nett radiation, minimum and maximum temperatures as well as the
Turc, Penman, Blaney & Criddle and Thornthwaite metereological formulae.
Furthermore the Class A-pan provides the simplest way to predict evapotrans-
piration and is presently a commonly used aid for scheduling irrigation.
Although many other expensive and complicated instruments are available to
scientists for programming water applications, tensiometers offer the best
alternative to the Class A-pan. The functioning, advantages and disadvan-
tages as well as applicability of tensiometers in viticulture are well-docu-
mented (Piaget, 1975; Van Zyl, 1981; Van Zyl & Weber, 1981; Van Zyl &
Booysen, 1983).

Irrigation Requirements of Grapevines

In South Africa different sets of crop factors have been in use for the conversion of class A-pan evaporation to evapotranspiration of grapevines shown in the following Table:

Month	Wine grapes[1]		Table[2] Grapes
	Limited Irrigation	Intensive Irrigation	
May - Sept.	0,20	0,20	0,10
Oct.	0,20	0,30	0,15
Nov.	0,25	0,40	0,20
Dec.	0,25	0,40	0,30
Jan.	0,25	0,40	0,42
Feb.	0,25	0,40	0,35
March	0,20	0,30	0,25
April	0,20	0,20	0,20

[1] Van Zyl (1981)

[2] Van Rooyen (1980)

These crop factors are valid for irrigation systems wetting the total surface area, but not for localized irrigation. Crop factors for vines increased from low values early in the season due to small total leaf areas per vine, to maxima between November and February. Other researchers also reported crop factors for grapevines namely, 0,22 - 0,56 from early season to late season (Stanhill 1962), 0,5 - 0,8 from early to late season according to Safran (Smart & Coombe, 1983) and a seasonal average of 0,27 - 0,35

(Nieuwoudt, 1965). The large variation in crop factors reported by the different researchers illustrate the many factors which play a role in determining crop factors. It was found that crop factors for grapevines were significantly affected by trellising system (Van Zyl & Van Huyssteen, 1980), the soil water regime (Van Rooyen, Weber & Levin, 1980; Van Zyl & Weber, 1981) and irrigation system (Smart, Turkington & Evans, 1974). Furthermore, water use varied with plant vigour as well as between cultivars (Bravdo, Lavee & Samish, 1972). Fregoni (1975) concluded that the most productive vineyards are not only the most vigorous, but also the most water demanding. Fregoni (1975) considered a consumption of 100 dm^3 of water through transpiration necessary for the production of 1 kg dry material. Many reports in literature with regard to consumptive water use and irrigation requirements of grapevines are not accompanied by ambient evaporation data and can therefore not be evaluated properly (Hendrickson & Veihmeyer, 1951; Kasimatis, 1967; Smart & Coombe, 1983).

Van Zyl (1981), using crop factors and long term evaporation data, calculated irrigation requirements for the different viticultural areas in South Africa as well as irrigation frequencies and application quantities for flood and sprinkle irrigation.

Due to its relative novelty and the localized nature of the water applications, special attention should be given to some aspects of trickle irrigation. Scheduling of irrigation becomes a more complicated matter when trickle irrigation is considered since the irrigation frequency and application rate are functions of such factors as soil infiltration rate, soil water holding capacity, soil aeration, leaching requirement, root-zone volume, evapotranspiration rates and dependable water supply (Elfving, 1982).

Nevertheless, Class A-pan evaporation together with crop factors have been used successfully to schedule trickle irrigation. However, in converting evaporation units to volume units some researchers used total land area assigned to each plant (Black & Mitchell, 1974; Willoughly & Cockroft, 1974), some used the area covered or shaded by the canopy (Kenworthy, 1972) and others only used the area of land actually wetted by the tricklers (Black, 1971).

In South Africa irrigation requirements for tricklers are obtained from a general nomogram which makes provision for class A-pan evaporation and the estimated area of leaf surface (Van Zyl, 1981). From Australia it was reported that trickle irrigation, either daily or on alternate days, with a crop factor of 0,40 produced grape yields comparable to those of furrow irrigated vines at a crop factor of 0,50 (Smart, Turkington & Evans, 1974). Yield was decreased slightly by reducing the crop factor for tricklers to 0,20. It was concluded that benefits from limited supplies of irrigation water will be maximal if applications are frequent and at a low rate. In a more recent study McCarthy, Cirami & McCloud (1983) compared Shiraz vines without irrigation to a trickle treatment at crop factors of 0,20 and 0,37 (first season) and 0,22 and 0,36 (second season). The higher crop factor resulted in a significant increase in yield and growth compared to 0,2 (the dryland control performed poorer than both irrigated treatments), but irrigation had adverse effects on wine quality parameters at the higher crop factor.

Many studies showed improved water use efficiencies for trickle irrigation compared to conventional irrigation techniques (Elfving, 1982). Large water savings of up to 85% during the first four years were achieved with daily

trickle on young apple trees compared to sprinkler irrigation every two weeks. Similarly, the saving of water with tricklers versus flood and sprinkler irrigation was the largest in a young vineyard, viz., 37%, 44% and 22% in the first, second and third years after planting (Peacock et. al., 1977). Water use efficiencies of flood and sprinkler plots improved as root growth approached full development.

Trickle Irrigation Frequencies

Flood and sprinkler irrigation are traditionally applied at a low frequency; they involve the application of large volumes of water within a short time and on a large soil area to create a soil reserve which can provide for plant requirements for as long as possible. In contrast, micro-jets and tricklers are operated at high frequencies, low volumes and at high soil water potentials and even at free water levels (Miller, 1967; Goldberg, Rinot & Karu, 1971; Levin, Assaf & Bravdo, 1974). Optimum irrigation frequencies for tricklers depend on soil infiltration rate, soil water holding capacity and root zone volume (Elfving, 1982). The limited water holding capacities of sandy soils dictate very frequent irrigations of even three to five times per day, as is the case in the Hexrivier Valley in South Africa. In heavier soils frequent irrigations may create a localised oxygen deficiency (Elfving, 1982). In general, oxygen deficiency can become limiting under too wet conditions while reduced soil matrix potential can reduce soil water availability (Phene & Beale, 1976). Jobling (Elfving, 1982) recommended irrigation frequencies ranging from pulse irrigation to once every 6 - 8 days, depending on the evaporative demand and the soil waterholding capacity.

Wetting Pattern

With trickle irrigation only a portion of the soil volume around each plant is irrigated and consequently roots will be restricted to this wetted volume in arid or semi-arid areas (Black, 1976). In cases where mature trees (or vines) are converted to trickle irrigation, root systems can adapt quickly (within 2 seasons) to the new irrigation method by proliferating in the wet soil volume. Root concentrations of fruit trees increased four to five fold under tricklers (Harrison & Myers, 1974; Willoughly & Cockcroft, 1974; Goode, Higgs & Hyrycz, 1978) and Black (1976) estimated that such an increase in rooting would increase the proportion of the root system supplied with water to more than 60% and the efficiency of water uptake to between 90 and 94% compared to fully watered trees. Black (1976) postulated that the minimum size of the wetting pattern, when converting mature trees to trickle, should be such that 25% of the root system is supplied with water. He also considered the proportion of the root system that should be watered of more importance than the proportion of the soil volume. Uys (1978), however, recommended that the wet area under tricklers at a depth of 0,30 m should cover between 25% and 50% of the total area in order to ensure an adequate soil water reservoir for grapevine roots.

The volume of wetted soil under tricklers is not only dependent on soil type, but also upon factors such as application rates, volume of water applied and time of application (Black, 1976). Insufficient storage of water in the soil can be overcome by pulse-irrigation, more than one trickler outlet per plant and by taking advantage of the ability of plants to absorb free water from the soil profile. The latter aim can be achieved by irrigating during daylight hours when water uptake and transpiration take place at a high rate (Black, 1976).

Restriction of root development to a specific soil volume imposed by trickle irrigation may have several important implications for plant growth. Confinement of roots in a small volume increases the drought sensitivity of a plant and causes a more rapid fluctuation in soil water and nutrient levels which in turn demand sound irrigation and fertilization practices.

The research described in this chapter mainly concerns water in the soil although it was an integral part of the greater irrigation experiment at Robertson. The objective was to (a) determine irrigation requirements of wine grapes in the Breede River Valley, (b) to determine irrigation frequencies at different irrigation regimes and (c) to evaluate methods and irrigation systems by which water can be saved. This information can contribute towards better irrigation scheduling and improved irrigation system design.

MATERIALS AND METHODS

Based on a pedological survey and the determination of soil physical proper-
ties (see Chapter 4), the experimental vineyard at Robertson was divided in-
to two parts with regard to irrigation scheduling. Plots in replicate group
1 - 3 were layed out on a sandy loam soil (Hutton from; Maintegwe series,
refered to as 'Hutton' in the text) and those in replicate group 4 - 6 on a
sandy clay loam (Hutton, Shigalo series in association with an Oakleaf soil,
Letaba series, refered to as 'Oakleaf' in the text). The monitoring of soil
water status, sampling of the soil as well as the application of irrigation
treatments were carried out on both soils separately.

Before commencement of the irrigation trial, undisturbed soil cores of ca.
69 cm^3 were taken in triplicate on 20 representative plots from the follo-
wing four soil layers: 0 - 0,25 m; 0,25 - 0,50 m; 0,50 - 0,75 m; 0,75 -
1,00 m. The average soil depth was 1 metre. Undisturbed soil cores were
obtained with the aid of a special auger into which brass cylinders fitted
closely. The auger was hammered to the desired depth in wet soil and the
cylinders with its content of undisturbed soil removed carefully. These
cores were then carefully trimmed to the exact size of the cylinders. Bulk
densities (Blake, 1965) were also determined (300 cm^3 cylinders) in close
proximity to the sampling positions of the smaller undisturbed soil cores.

Soil water retention curves were constructed with data obtained by subjec-
ting the undisturbed soil samples, after saturation, to a range of increa-
sing pressures up to 1 500 kPa (permanent wilting point) in a pressure plate
apparatus according to standard techniques. In situ field water capacity
(FC) was determined on 20 representative plots during the dormant season of
the young vines. This field method involved saturation of the soil, cove-
ring the surface to prevent evaporation and monitoring soil water redistri-

bution both gravimetrically and with the aid of tensiometers until drainage of free water became negligigle. The waterholding capacity (d) of the soil was calculated by the formula:

$$d \text{ (mm)} = \frac{(FC - PWP) \times \varrho_b \times D}{100}$$

where,

FC = Soil water percentage by mass at field water capacity.

PWP = Soil water percentage by mass at permanent wilting point.

D = Thickness of the relevant soil layer (m).

ϱ_b = Bulk density (kg m^{-3}).

Water Supply and Monitoring of the Soil Water Status

On plots of nine treatments water was applied by micro-jets with a 280° wetting pattern covering most of the surface area. The micro-jets were installed upright 0,30 m above ground level with a spacing of 3,0 m x 3,0 m and a water application rate of 6,8 mmh^{-1}. Three further treatments consisted of trickle, sprinkle or flood irrigation (see Chapter 4, Table 1 for detailed description of treatments). Trickle irrigation was applied at a rate of 4 dm^3 h^{-1} and the spacing between tricklers was 1m. Sprinkle irrigation was carried out using under-vine sprinklers, while flood irrigation took place in 2m wide furrows with the vine rows down the middle. Furrow lengths were restricted by the lengths of plots i.e. 34,5 m. Each experimental row was buffered from its neighbours by four buffer rows of 3m wide, thus resulting in a plot size of 517,5 m^2. Irrigation quantities were determined using the following relationship:

volume of water (dm^3) = depth of water (mm) x plot size (m^2)

The following water distribution efficiencies (Cu-values) were assumed when calculating the gross irrigation quantities: Trickle irrigation = 100%; micro-jets = 90%; sprinkle and flood irrigation = 80%. A further adaptation was made to provide for the lateral distribution of water under tricklers and will be described later. Volumetric valves were installed on each plot in order to apply the correct quantity of irrigation water.

Mercury type tensiometers were prepared and calibrated in the laboratory before installation. These meters were installed on 22 plots i.e. 11 plots on each of two replicates of the randomized block design, and at four depths on each plot viz., o,15 - 0,20 m; 0,35 - 0,40 m; 0,55 - 0,60 m and 0,85 - 0,90 m. The tensiometers were placed in the vine row with the deepest instrument in the middle between two vines and the shallowest one 0,30 m distant from the vine. Special care was taken on trickle plots to ensure that all four tensiometers were at equal distances from the trickler. It was further reasoned that the soil directly below a trickler would be too wet, and in the middle between two tricklers, too dry to be representative of the soil water status to which the grapevines were subjected. Consequently all tensiometers were spaced 0,25 m from a trickler.

As a rule, tensiometer readings were taken three times weekly, but more often when an irrigation on a specific plot was imminent. Readings were taken at 08h00, commenced in September (prior to bud burst) and continued until the end of March (harvesting). During two years, tensiometers were also read during winter time. On plots which became too dry for the functioning of tensiometers, soil water content was determined either gravimetrically, or with a neutron moisture meter calibrated according to the method of Karsten & Haasbroek (1973).

Soil Water Regimes

Soil water potentials as indicated by tensiometers were transformed to soil water content (mm) using the soil water retention curves. A Soil water deficit (FC minus soil water content) was then calculated for each soil layer, summed over the total soil depth and the soil water regime calculated as follows:

$$\text{Water regime (\%)} = \frac{d - (WD1 + WD2 + WD3 + WD4)}{d} \times 100$$

where,

> WD = Water deficit for the 4 soil layers (mm).
> d = Water holding capacity of the profile (mm).

When the predetermined moisture regimes on the different treatment plots were reached, an irrigation was applied. The quantity of water to be applied was calculated with the aim of wetting the entire soil volume. However, adaptations were made on trickler plots in order to accommodate the water distribution pattern under tricklers.

Crop Factors:

A class A evaporation pan and a rain guage were installed adjacent to the vineyard to provide data for the calculation of crop factors. Other climatic data were also available from a weather station 800m from the experimental vineyard.

Crop factors were calculated for all treatments using the well-known

formula:

Crop factor = Et/Eo

where Et = Evapotranspiration (mm).
       Eo = Evaporation from the Class A pan (mm).

Evapotranspiration was determined by calculating the decrease in soil water content over a period of time. Crop factors were calculated for the entire period between two successive irrigations in order to avoid the large short term variation in crop factors. Only rainless periods were used due to the uncertainty as regards the effectivity of rainfall.

Water Distribution under Tricklers

The distribution of water in the soil under tricklers was determined by visual observation (colour differences) as well as gravimetrically. The first method comprised the digging of profile pits and plotting of the areas of wet, moist and dry soil against the profile wall on graph paper. Secondly the soil water status in the immediate vicinity of the trickler was determined gravimetrically in order to get a more accurate picture of the soil water distribution. The soil was sampled at 0,20 m depth increments down to 1 metre, starting directly under the trickler and proceeding outwards with 0,25 m increments on both sides of, and perpendicular to the trickler line. These soil samples were also kept for measurement of electrical resistance of the soil paste in order to evaluate salt leaching around the trickler. This investigation was conducted in mid-summer at a stage when equilibrium had already been established between dry and wet soil. Soil sampling was carried out in triplicate on each of the five trickler plots.

RESULTS AND DISCUSSION

Water Holding Capacity of the Soil

In situ measurements of FC - the upper boundary of plant available water - were complicated by the prolonged redistribution of soil water following saturation of the soil. Although slow, drainage still continued two weeks after the measurements commenced (Fig. 1). However, it was assumed that drainage became negligible after 200 hours and the average water content of the three last gravimetric water determinations were taken as FC.

Tensiometer readings gave a more reliable indication when FC had been approached than gravimetric water determinations (Fig. 1). In situ FC was attained at soil water potentials between - 5 and - 8 kPa depending on the site, but on average (for the experimental vineyard as a whole) - 6 kPa indicated FC.

Values for the upper and lower limits of available water as well as the total available water for the soil profile are presented in Table 1. The difference in soil between the two parts of the experimental vineyard is clearly reflected in the total available water namely 151mm and 121mm on the sandy loam and the sand clay loam respectively. Irrigation frequencies varied accordingly.

Quantities and Frequencies of Irrigation

Irrigation frequencies were on average 25% lower on the three replicate plots of the Hutton soil than on the Oakleaf soil. This deviation could be

mainly ascribed to the 20% difference in total available water, and partly to a poorer shoot growth (pruning mass = 1,63 kg/vine) on the soil containing the high fine sand fraction namely the Hutton in comparison with the Oakleaf soil (pruning mass = 2,15 kg/vine).

Irrigation intervals were shortest for the trickler plots (Table 2). Although an average interval of 3,3 days were found for trickle irrigation, during December to February, three trickle irrigations per week (Monday, Wednesday and Friday) were necessary to maintain a 90% soil water regime. Due to the small reservoir of soil water on trickle plots, the soil water potential decreased deceptively fast and could change from FC to a stressed situation within two days (Fig. 2).

Micro-jet irrigation at a 90% water regime needed a frequency of one water application every 4,8 days on the Oakleaf and 5,6 days on the Hutton soil. From a practical point of view, two micro-jet irrigations per week during the peak period (November - February) would be sufficient to keep the soil water content between 90% and FC on soils similar to those of the experimental vineyard.

A 70% water regime (T3) could be maintained irrigating every 10 to 12 days depending on the soil type while a 50% regime (T2) required one irrigation every 16,3 days (Oakleaf) or 22,5 days (Hutton) (Table 2). The irrigation intervals for sprinklers (T11) and flood irrigation (T12) did not differ significantly from those of micro-jets although the 14 day interval for sprinklers on the Oakleaf soil seems to be too short. The three irrigation systems which operated at a 50% regime (micro-jets, sprinklers and flood) had a mean irrigation interval of 16 days on the Oakleaf soil and 22 days on the Hutton. The irrigation interval (45 days) of the 25% soil water regime (T1) was too low and led to a decrease in plant growth.

Nett quantities of irrigation water applied to the different treatment plots during four seasons appear in Table 3. Although those quantities were high - between 550 mm and 600 mm for fully irrigated treatments such as T2, T3, T4, T11 and T12 - it should be borne in mind that Colombar has a very long growing season namely, from middle September to the end of March. There were no significant differences in irrigation requirements among the 50% (T2), 70% (T3) and 90% (T4) soil water regimes. The 25% regime (T1) received significantly less water than its three counterparts in the T1 - T4 group of treatments. Signs of water stress in T1 vines (see Chapter 4) proved that the 335 mm of irrigation water applied to T1 plots, was too low.

Vines on T5 plots, scheduled to be stressed during the bud burst to flowering stage, received practically the same irrigation quantity as T3 vines which were maintained at a 70% regime without additional stress during any particular phenological stage. The T5 plots, in fact, reached the 25% soil water regime in only one season. During the other four seasons commencement of flowering dictated water applications at a stage when the soil water regime was 44% on the Oakleaf soil and 47% on the Hutton soil on average. The low irrigation requirement before flowering was a result of the low evaporation demand and small leaf area in the early season. The irrigation frequency during this period should consequently be low and it should not be necessary to apply any water on soils comparable to those of the experimental vineyard before the end of October immediately prior to flowering, provided that the soil was at FC at bud burst.

Water stress during particular phenological stages e.g. flowering and fruit set (T6), the lag phase of berry growth (T7) or during ripening (T8), reduced the quantity of irrigation water significantly from a practical viewpoint (not significant statistically, compared to T2, T3 and T4) although indications were that yields were also deleteriously affected especially by

stress during fruit set. On T8 plots it was found that prolonged water stress during ripening led to loss of berry turgidity. Treatment 9 which, due to autumn rains, repeatedly missed its objective of investigating the effect of post-harvest irrigations, was changed to allow water stress in part of the root zone during ripening. This new treatment involved weekly irrigations to replenish the soil water deficit in only the upper two soil layers, but allowing the subsoil (0,50 - 1,00 m) to dry out (Fig. 3). Since the vines were forced to utilise reserve soil water from the two deeper layers, 52,7% and 43,7% irrigation water could be saved in the ripening period by this method compared to the irrigation quantities required to maintain the entire soil depth at a 70% water regime (means of T3 and T5) in the 1981/82 and 1982/83 seasons respectively. Neither the yield nor the sugar and acid contents were deleteriously affected by stress in the subsoil (Table 4). Although it can be reasoned that such a practice would leave the soil dry and the grapevines in need of a large post-harvest irrigation, experience showed that rain can normally be expected during the post-harvest period in April (long term average rainfall at Robertson for April = 22,0mm.

Regarding the nett quantity of irrigation water, sprinkle and flood irrigation did not differ from each other or from micro-jets (Table 3). However, trickler plots had an irrigation requirement of only 414,4 mm in comparison to the 595,4 mm of micro-jets, the 577,2 mm of sprinklers and 566 mm of flood irrigation. Trickle irrigation thus saved 30,3%, 28,2% and 26,8% irrigation water compared to micro-jets, sprinklers and flood irrigation respectively. This saving could be accomplished without a loss in yield, and can be attributed to the fact that only 33% of the total soil volume was wetted by the tricklers. Although 65% of the roots were confined to this wet area living roots were found in the un-irrigated soil volume between rows. Gravimetric determination of water contents confirmed water utili-

zation in this soil volume, even though the soil was at, or even below PWP. This observation confirmed that of Black & West (Black, 1976).

This 'unused' soil volume between rows was in most years brought to FC by winter rains, and this water was extracted by the vines during the growing season. Consequently, to the 414,4 mm of irrigation water, an additional 81,3 - 101,4 mm should be added when calculating the total quantity of water that may be available to the vines. This additional quantity (y) can be calculated by multiplying the water holding capacity of the soil (d) by the fraction (0,67) not wetted by the tricklers e.g.,

$$y = 0,67 \ d$$

Application of this approach, increased the quantity of water available to vines on trickler plots to 494,8 - 514,9 mm, depending on the soil type. These quantities agree with the approximately 500 mm which Van Zyl & Van Huyssteen (1984) estimated to be the water requirement of grapevines in the Western Cape. In this experiment, deviation from this quantity seems to be due to either an unfavourable water stress in some treatments e.g. T1, T6, T7, T8 or to an oversupply which can result in drainage losses or too luxurious growth. The average rainfall during the growing season amounted to only 75,3mm for the period 1978/79 - 1982/83. (The data for 1980/81 could not be used due to a rainstorm which distorted results). Only 53,9% (40,6mm) of the rain occurred in showers of more than 10mm. Therefore, although rain was not totally absent, its contribution to soil water replenishment was minimal.

Moisture and Salt Distribution under Tricklers

Initially many problems were encountered concerning the infiltration of water under tricklers. Water ponded on the soil surface and ran into the tractor tracks where tractor and implement traffic aggrevated the situation by creating impenetrable hollows. Water evaporated from these pools without being able to infiltrate. An application of 15 t ha^{-1} of gypsum

improved water infiltration, but the problem remained, although to a lesser extent in isolated spots.

Visual mapping of the soil water content in a profile wall in the experimental vineyard, revealed a maximum lateral water distribution of approximately 0,50 m (Fig. 4). This illustration also shows that irrigation scheduling with the help of tensiometers prevented water loss though drainage of free water. Although the boundaries between the dry, moist and wet soil was often diffuse, gravimetric determination of soil water content during a second season, confirmed the result of visual mapping (Fig. 5). The soil water was not always evenly distributed in the wet zone due to clods and non-homogeneous soil mixing during soil preparation. The root distribution pattern, with 65% of the total number of roots within a 0,50 m distance from the trickler, conformed to the soil water distribution pattern.

The change in the electrical resistance of the soil paste with depth and with increasing lateral distance from the tricklers illustrated leaching of salts from the trickled zone (Fig. 6). It was evident that the soil volume close to the tricklers had a higher resistance than further away e.g. 520 Ω at 0,50 m from tricklers as against 382 Ω at a 0,50 - 1,00 m distance.

Soil Water Regimes

Examples of soil water retention curves used to convert tensiometer readings to soil water content for the calculation of irrigation quantities are depicted in Fig. 7. On average 68,3% to 74,5% of the total available water was stored at a soil water potential higher than - 80 kPa on the sandy clay loam and the sandy loam soil, respectively. It was therefore possible to use tensiometers for the scheduling of irrigations even on plots maintained

at a 50% soil water regime (Fig. 8). On T2 plots the mean soil water poten-
tial decreased to - 44 kPa before the next irrigation was due (Table 5).
The 70% soil water regime (T3) required irrigations at a soil water poten-
tial of - 19 kPa which was indicated by much smaller peaks (Fig. 9). The
fluctuation in soil water potential was still less on plots maintained at a
90% soil water regime (T4) as was evident from Fig. 10. In watering T4 plots
with small quantities (10 - 12 mm) at a time, problems were encountered to
distribute this small quantity evenly throughout the profile. The two shal-
lower soil layers, 0 - 0,25 m and 0,25 m - 0,50 m, remained approximately at
FC, but water deficits often occurred in the deeper layers (Fig. 11). The
small quantity of water applied on the surface, was in most cases intercep-
ted by roots before it could permeate to the subsoil. Drying out of the
subsoil of T4 plots could only be overcome by heavier irrigations from time
to time (Fig. 11). Despite this difficulty, T4 plots were on average irri-
gated at a soil water potential of - 10,8 kPa. Similarly, fluctuations in
soil water potential was low on trickler plots which were irrigated at -11,4
kPa. Due to its small reservoir of soil water, soil water potentials de-
creased at a very fast rate (Fig. 2). This rapid change in soil water po-
tential stressed the general importance of sound irrigation management in
the case of trickle.

Contrary to what is often found, the soil water was depleted very uniformly
from the different soil layers on most plots (Fig. 12). Very often the se-
cond layer dried out at a faster rate than the surface soil layer, but water
was also extracted from the deepest layers at a fast rate. The uniform de-
pletion of water with depth was undoubtedly a reflection of the good root
distribution throughout the soil profile.

Crop factors:

Similar to the irrigation requirement data, crop factors calculated for micro-jets at the three soil water regimes of 50%, 70% and 90% as well as for sprinkle and flood irrigation were not significantly different (Table 6). During October the crop factor (0,29) was on average significantly less than during the following five months. Crop factors increased sharply from october to November (from 0,29 - 0,43 on average), but was quite stable from then onwards with no distinct peak in any one month. The crop factors increased on average from 0,43 in November to a maximum 0,492 in January and 0,496 in February. Surprisingly the crop factor for March was 0,478 which is higher than the 0,30 accepted previously (Van Zyl, 1981) for wine grapes. With the exception of October values, the crop factors in Table 6 (trickle irrigation excluded) are on average 20% higher than the factors for wine grapes in use presently.

The uncertainty to date, as regards the correct crop factor values for trickle irrigation in vineyards has been alleviated and the present data (Table 6) are the first to be calculated for grapevines in South Africa. These values are significantly lower than those for the three other irrigation systems and in good agreement with Australian values of 0,30 used for grapevines throughout the season (Smart, Turkington & Evans, 1974) and 0,30 - 0,40 used for trickle with sewage effluent on Shiraz (McCarthy, 1981).

Crop factors during the dormant season of grapevines are largely dependent on factors such as cover crops and rainfall pattern, and was previously accepted as 0,20 from April to September. Values calculated from data obtained in the experimental vineyard at Robertson during one dormant season merely confirmed that a crop factor of 0,20 is applicable as a guideline to irrigation requirements of grapevines during winter.

CONCLUSION

An analysis of results obtained over a five year period in an irrigation trial with wine grapes, led to the conclusion that trickle irrigation requires a high application frequency of at least three times weekly, but preferably once every two days on the red Hutton and Sterkspruit soils, representative of the Breede River Valley. This short frequency is dictated by a small soil reservoir. The lateral water distribution was adequate for a wet strip of only 1 m in diameter. The majority of roots was confined to this wet area. Roots found in the dry inter-row area were still alive and could exploit the soil for water during spring when the total soil volume had been replenished by rain.

Micro-jets, wetting a bigger soil volume than tricklers, were able to maintain a 90% soil water regime at an irrigation frequency of two applications per week. A 70% soil water regime could be maintained by one irrigation every 10 - 12 days, while water applications every 16 days on an Oakleaf and every 22 days on a Hutton were required for a 50% water regime during the period of peak water consumption. Plots subjected to a 25% soil water regime had such a low frequency of water application that growth was retarded.

Micro-jets, sprinklers and flood irrigation did not differ with regard to either irrigation frequency or nett quantity of water required. However, under less optimal conditions than those of the experiment, the gross quantity of irrigation water required would be higher for the latter two systems. Based upon the 50%, 70% and 90% soil water regimes, it was clear that a late cultivar like Colombar has a nett irrigation requirement of 594 mm per season at Robertson. A water saving of 25 - 30% was obtained with trickle irrigation compared to the three other systems. The reduction in

irrigation quantities of treatments which maintained a 25% regime either throughout the season, during fruit set or during ripening is not justifiable due to its deleterious effect on berry size. The early vegetative period, commencing with bud burst and ending at flowering, appeared to be a stage when the water requirement of grapevines is low and irrigations can be withheld without causing vine water stress or a decrease in production.

Mild water stress during ripening by only irrigating the upper part of the soil profile and allowing water depletion in the deeper root zone, proved to be most successful. Although no improvement as regards must quality was found, the grape yield remained unaffected while saving 44% - 53% of the water needed by treatments which were fully irrigated during ripening.

Maintaining the drier soil water regimes posed few problems, but the subsoil of the wet T4 treatment plots tended to dry out when small quantities of water were applied. Downward movement of these small quantities was slow and the water was apparently intercepted before it could permeate to the deeper soil horisons. This problem could only be rectified by occasional heavier water applications.

Due to the small wetted soil volume, the soil water potential decreased rapidly under tricklers. This characteristic of trickle irrigation stresses the fact that it is more practical to follow a fixed irrigation schedule with tricklers (and micro-jets) e.g. to irrigate three times per week, and to only use tensiometers to regulate irrigation quantities. Soil water extraction occurred very uniformly with depth, irrespective of the irrigation system. The good root distribution is most certainly the reason for this favourable water depletion pattern.

Crop factors increased sharply from October to November, but remained quite

stable from then onwards. These factors were similar for micro-jets, sprin-
klers and flood irrigation and were on average 20% higher than those recom-
mended presently. The crop factor for March was found to be 0,48 in compa-
rison with 0,30 which was accepted until present. The crop factor for late
grape cultivars like Colombar should be increased during March, but only
from November - February for other cultivars, on the well-drained soils of
the irrigated areas in South Africa. A crop factor of 0,30 was obtained for
tricklers from November to March.

LITERATURE CITED

BLACK, J.D.F., 1971. Daily flow irrigation. Victoria Dept. Agr. Leaflet: H191.

BLACK, J.D.F., 1976. Trickle irrigation - a review. Hort. Abstr. 46, 1 - 7, 69 - 74.

BLACK, J.D.F. & MITCHELL, P.D., 1974. Changes in root distribution of mature pear trees in response to trickle irrigation. Proc. 2nd Int. Drip Irrig. Congr., July 7 - 14, 1974, San Diego, Univ. of California, Riverside, 437 - 438.

BLAKE, G.R., 1965. Bulk density. In: Methods of soil analysis Part I. (Eds. C.A. Black, D.D. Evans, J.L. White, L.E. Ensminger + F.E. Clark) Agron. Series no. 9, 374 - 390. Am. Soc. Agron. Madison Wisconsin.

BLANEY, H.F. & CRIDDLE, W.D., 1950. Determining water requirements in irrigated areas from climatological and irrigation data. USDA Soil. Cons. Service, Tp - 96, Washington, DC.

BRAVDO, B., LAVEE, S. & SAMISH, R.M., 1972. Analysis of water consumption of various grapevine cultivars. Vitis 10, 279 - 291.

CLAASSEN, F.A., 1969. Inleidende studies tot die opstel van 'n besproeiingsprogram by wingerd. MSc (Agric.) thesis, Univ. Stellenbosch.

DU PISANI, A.L., 1970. Methods for determining water requirements. Decid. Fruit Grower 20, 245 - 247.

ELFVING, D.C., 1982. Crop response to trickle irrigation. In: J. Janick (ed.). Horticultural Reviews 4, 1 - 48. AVI Publishing Co., Westport, Connecticut.

FREGONI, M., 1977. Irrigation des vignobles. Problems de physiologie, de biochimie de génétique, d'agronomie, de technologie et d'economie. Bull. Off. int. Vin 50 (551), 3 - 19.

GOLDBERG, S.D., RINOT, M. & KARU, N., 1971. Effect of trickle irrigation intervals on distribution and utilization of soil moisture in vineyard. Proc. Soil Sci. Soc. Am. 35, 127 - 131.

GOODE, J.E. HIGGS, K.H. & HYRYCZ, K.J., 1978. Trickle irrigation of apple trees and the effects of liquid feeding with NO_3^- and K^+ compared with normal manuring. J.Hort.Sci. 53, 307 - 316.

HARRISON, D.W. & MYERS, J.M., 1974. Drip irrigation design criteria for the crops in Florida and other humid regions. Proc. 2nd Int. Drip Irrig. Congr., July 7 - 14, 1974, San Diego, Univ. of California, Riverside, 33 - 37.

HENDRICKSON, A.H. & VEIHMEYER, F.J., 1951. Irrigation experiments with grapes. Bull.Calif. Agric.Exp.Stn. 728, 1 - 31.

KARSTEN, J.H.M. & HAASBROEK, F.J., 1973. A new method of calibrating the neutron moisture meter and a correction for the effect of soil bulk density. Agrochemophysica 5, 35 - 40.

KASIMATIS, A.N., 1967. Grapes. In: R.M. Hagan, H.R. Haise & T.W. Edminster (eds.). Irrigation of Agricultural lands. Agron. Series 11, 719 - 739. Am. Soc. Agron., Madison, Wisconsin.

KENWORTHY, A.L., 1972. Trickle irrigation - the concept and guidelines for use. Mich. State Univ. Agric. Expt. Sta. Res. Rpt. 165.

LEVIN, I., ASSAF., R. & BRAVDO, B.A., 1974. Soil moisture distribution and depletion in an apple orchard irrigated by tricklers. Proc. 2nd Int. Drip Irrig. Congr., July 7 - 14, 1974, San Diego. Univ. of California, Riverside 252 - 257.

McCARTHY, M.G., 1981. Irrigation of grapevines with sewage effluent. I. Effects on yield and petiole composition. Am.J.Enol.Vitic. 32, 189 - 196.

McCARTHY, M.G., CIRAMI, R.M. & McCLOUD P., 1983. Vine and fruit response to supplementary irrigation and canopy management. S.Afr.J.Enol.Vitic. 4, 67 - 76.

MILLER, D.E., 1967. Available water in soil as influenced by extraction of soil water by plants. Agron.J. 59, 420 - 423.

NIEUWOUDT, A.D., 1965. Besproeiing in die Olifantsriviervallei. Tegniese Mededeling no. 47, Dept. Agricultural Technical Services, Pretoria.

PEACOCK, W.L., ROLSTON, D.E., ALJIBURY, F.K. & RAUSCHKOLB, R.S., 1977. Evaluating drip, flood and sprinkler irrigation of wine grapes. Am.J. Enol. Vitic. 28, 193 - 195.

PENMAN, H.L., 1948. Natural evaporation from open water, bare soil and grass. Proc. Roy. Soc. London, Ser. A 193, 120 - 146.

PHENE, C.J. & BEALE, O.W., 1976. High frequency irrigation for water-nutrient management in humid regions. Soil Soc. Am. J. 40, 430 - 436.

PIAGET, J., 1975. What tensiometers are all about. The Decid. Fruit Grower 25, 64 - 65.

SMART, R.E. & COOMBE, B.G., 1983. Water relations of grapevines. In: Water deficits and plant growth (Ed. T.T. Kozlowski) VII, 137 - 196. Academic Press, New York.

SMART, R.E. TURKINGTON, C.R. & EVANS, J.C., 1974. Grapevine response to furrow and trickle irrigation. Am.J.Enol.Vitic. 25, 62 - 66.

STANHILL, G., 1962. The control of field irrigation practice from measurements of evaporation. Isr. J. Agric. Res. 12, 51 - 62.

THORNTHWAITE, C.W., 1954. An approach toward a rational classification of climate. Geogr. Rev. 38, 55 - 94.

TURC, L., 1953. The soil water balance: Interrelations of rainfall, evaporation and runoff. Afr.Soils 3, 139 - 172.

UYS, W.J., 1978. Ontwerp en bestuur van drup en mikrospuitbesproeiingstelsels. Ingenieurswese C. 17/78. Dept. Agricultural Technical Services, Silverton.

VAN DER WESTHUIZEN, M., 1964. Inleidende studies tot die bepaling van verdamping en evapotranspirasie. D.Sc. thesis, Univ. O.F.S.

VAN ROOYEN, F.C., 1980. The water requirements of table grapes. The Decid.

Fruit Grower 30, 100 - 105.

VAN ROOYEN, F.C., WEBER, H.W. & LEVIN, I., 1980. The response of grapes to a manipulation of the soil plant atmosphere continuum. II Plant-Water relationships. Agrochemophysica 12, 69 - 74.

VAN ZYL, J.L., 1981. Waterbehoefte en besproeiing. In: J.D. Burger & J. Deist (eds.). Wingerdbou in Suid-Afrika. VORI, Stellenbosch, South Africa, pp. 234 - 282.

VAN ZYL, J.L. & BOOYSEN, J.H., 1983. Praktiese toepassing van besproeiings-beginsels op die wingerde van Laborie. Wynboer 618, 52 - 57.

VAN ZYL, J.L. & VAN HUYSSTEEN, L., 1980. Comparative studies on wine grapes on different trellising systems: I. Consumptive water use. S. Afr. J. Enol. Vitic. 1 (1), 7 - 14.

VAN ZYL, J.L. & VAN HUYSSTEEN, L. 1984. Soil and water management for optimum grape yield and quality under conditions of limited or no irrigation. Proc. 5th Austr. Wine Industry Tech. Conf. 29 Nov. - 1 Dec. 1983, Perth, Western Australia. The Australian Wine Research Institute, Adelaide, South Australia, 25 - 68.

VAN ZYL, J.L. & WEBER, H.W., 1981. The effect of various supplementary irrigation treatments on plant and soil moisture relationships in a vineyard (Vitis vinifera var. Chenin blanc). S.Afr.J.Enol.Vitic. 2, 83 - 99.

WILLOUGHBY, P. & COCKROFT, B., 1974. Changes in root patterns of peach trees under trickle irrigation. Proc. 2nd Int. Drip Irrig. Congr.,

July 7 - 14, 1974 San Diego. Univ. of California, Riverside 439 - 442.

Table 1 a: Water holding capacities of different treatments plots on a Hutton soil (sandy loam).

Treatment	Field Capacity (mm/soil layer)				Permanent Wilting Point (mm/soil layer)				Available water (mm/soil layer)				Total Available Water (mm m^{-1})
	Soil Depth (m)				Soil Depth (m)				Soil Depth (m)				
	0–0,25	0,25–0,50	0,50–0,75	0,75–1,0	0–0,25	0,25–0,50	0,50–0,75	0,75–1,0	0–0,25	0,25–0,50	0,50–0,75	0,75–1,0	
T1	54,50	59,00	61,00	62,70	23,81	25,58	22,52	23,47	30,69	33,42	38,48	39,23	141,82
T2	64,20	62,30	74,00	77,50	23,95	21,73	38,94	41,20	40,25	40,57	36,06	36,30	152,18
T3	55,70	55,70	65,00	69,00	21,59	23,68	28,51	30,70	34,11	32,02	36,49	38,30	140,92
T4	62,20	56,00	56,40	59,50	20,05	20,20	22,56	26,90	42,15	35,80	33,84	32,60	144,39
T5	77,40	69,00	73,00	76,00	26,91	27,68	30,41	40,59	50,49	41,32	42,59	35,91	170,31
T10	64,80	65,70	70,20	76,80	23,94	27,60	27,71	40,56	40,86	38,10	42,49	36,24	157,69
T11	54,50	72,20	58,30	64,80	20,98	28,95	22,82	30,42	33,52	43,25	35,48	34,38	146,63
T12	64,50	67,50	76,30	79,00	24,29	28,98	37,20	40,06	40,21	38,52	39,10	38,94	156,77
Mean	62,23	63,43	66,78	70,73	23,19	25,55	28,83	34,24	39,04	37,88	37,94	36,49	151,34

Table 1 b: Water holding capacities of different treatment plots on an Oakleaf soil (sandy clay loam)

Treatment	Field Capacity (mm/soil layer)				Permanent Wilting Point (mm/soil layer)				Available Soil Water (mm/soil layer)				Total Available water (mm m^{-1})
	Soil Depth (m)				Soil Depth (m)				Soil Depth (m)				
	0-0,25	0,25-0,50	0,50-0,75	0,75-1,0	0-0,25	0,25-0,50	0,50-0,75	0,75-1,0	0-0,25	0,25-0,50	0,50-0,75	0,75-1,0	
T1	70,70	68,50	65,30	66,00	41,06	40,19	40,26	38,18	29,64	28,31	25,04	27,82	110,66
T2	83,00	72,20	74,00	79,30	52,97	43,86	44,45	47,56	30,03	28,34	29,55	31,74	119,66
T3	67,70	72,30	77,00	78,00	38,70	40,45	47,68	47,34	29,00	31,85	29,32	30,66	120,83
T4	72,00	69,80	72,30	65,50	42,39	43,51	44,08	42,88	29,61	26,29	28,22	22,62	106,74
T5	71,20	64,80	68,30	74,50	36,90	34,22	35,61	41,02	34,30	30,58	32,69	33,48	131,05
T6	67,40	73,50	74,30	73,70	32,53	43,94	39,21	37,08	34,87	29,56	35,09	36,62	136,14
T7	62,40	63,50	61,50	67,70	40,13	36,20	32,00	42,41	22,27	27,30	29,50	25,29	104,36
T8	72,30	63,70	65,60	67,00	44,56	37,50	38,42	40,32	27,74	26,20	27,18	26,68	107,80
T9	72,30	71,00	68,70	69,50	31,88	36,01	33,49	39,81	40,42	34,99	35,21	29,69	140,31
T10	77,00	70,00	76,00	79,50	42,48	42,06	46,57	44,34	34,52	27,94	29,43	35,16	127,05
T11	58,50	62,80	62,80	81,50	27,07	34,88	33,89	50,18	31,43	27,92	28,91	31,32	119,58
T12	65,60	67,00	62,80	74,00	30,57	34,95	30,64	41,50	35,03	32,05	32,16	32,50	131,74
Mean	70,01	68,26	69,05	73,02	38,44	38,98	38,86	42,72	31,57	29,28	30,19	30,30	121,34

Table 2: Mean irrigation intervals (days) of different treatments on two textural classes within the irrigation trial during the months of peak water consumption (Nov. - February).

Season	Sandy Loam Soil							Sandy Clay Loam Soil						
	T1	T2	T3	T4	T10*	T11	T12	T1	T2	T3	T4	T10*	T11	T12
1978/79	33,0	16,6	10,3	4,0	-	13,1	15,9	33,0	18,0	9,3	3,8	-	20,0	15,3
1979/80	50,0	17,4	9,8	4,1	3,2	14,3	13,9	49,0	18,5	14,4	4,8	3,2	23,3	22,8
1980/81	44,0	14,5	10,0	4,2	3,3	15,3	18,8	44,0	23,0	11,9	6,0	3,3	-	-
1981/82	54,0	15,7	10,1	5,7	3,6	12,4	18,6	54,0	24,8	12,5	7,4	3,6	24,5	21,8
1982/83	46,0	17,5	11,6	6,2	3,2	14,8	-	46,0	28,0	12,3	6,1	3,2	22,2	19,8
Mean	45,4	16,3	10,4	4,8	3,3	14,0	16,8	45,4	22,5	12,1	5,6	3,3	22,5	19,9

T1 - 25% soil water regime; micro-jets.
T2 - 50% soil water regime; micro-jets.
T3 - 70% soil water regime; micro-jets.
T4 - 90% soil water regime; micro-jets.
T10 - 90% soil water regime; tricklers.
T11 - 50% soil water regime; sprinklers.
T12 - 50% soil water regime; flooding.
* - Same schedule used for both soils.

Table 3:   Nett quantity of irrigation water (mm) applied to the different treatment
plots in an irrigation trial at Robertson

Treatment	1978/79	1979/80	1981/82	1982/83	Mean
T1	368,4	352,5	280,0	340,0	335,2
T2	634,3	695,2	529,4	523,2	595,5
T3	624,3	610,8	585,4	546,6	591,8
T4	618,9	667,7	589,8	505,2	595,4
T5	502,8	703,0	648,4	635,4	622,4
T6	457,7	480,9	372,0	393,4	426,0
T7	448,1	531,3	517,7	544,8	510,5
T8	555,1	462,3	439,3	476,7	483,4
T9	948,2	831,8	544,9	576,2	725,3
T10	434,1	561,6	340,9	321,0	414,4
T11	570,0	559,2	606,2	573,2	577,2
T12	772,5	509,4	496,6	485,6	566,0
D-Value (P $\leq$ 0,05)					196,5

Table 4: Effect of limited irrigation during the ripening period of Colombar grapes in comparison with treatment plots fully irrigated during the same period.

Season	Treatments at a 70% water regime	Consumptive Water Use during ripening (mm)	Grape Yield (kg/vine)	Sugar Content (°B)	Total Titratable Acidity (g dm^{-3})
1979/80: Before T9 was adapted	T3 (control)	220,7	18,29	18,1	9,44
	T5	213,9	18,46	18,1	9,74
	T9	242,3	16,68	18,4	9,44
	D-value (P ≤ 0,05)	NA	NS	NS	NS
1981/82: After adaptation of T9	T3 (control)	185,2	18,30	18,1	8,90
	T5	216,0	19,12	18,1	9,44
	T9	131,3	20,35	18,2	10,04
	D-value (P ≤ 0,05)	NA	NS	NS	NS
1982/83: After adaptation of T9	T3 (control)	153,8	23,23	18,0	8,40
	T5	201,4	23,23	17,9	8,48
	T9	123,6	25,13	17,8	8,48
	D-value (P ≤ 0,05)	NA	NS	NS	NS

NS — Not significant
NA — No statistical analysis

Table 5: Mean soil water potential at which the different irrigation treatments were irrigated during the 1978/79 – 1982/83 seasons.

Treatment	Soil Water Potential (kPa)				Mean
	0 – 0,25 m	0,25 – 0,50 m	0,50 – 0,75 m	0,75 – 1,00 m	
T2	–42,5	–59,4	–33,5	–39,2	–43,7
T3	– 9,9	–13,5	–22,8	–28,8	–18,8
T4	– 6,4	–11,8	–10,8	–14,1	–10,8
T5	–20,9	–15,3	–17,5	–15,6	–17,3
T7	–29,6	–28,4	–28,2	–25,2	–27,9
T8	–20,9	–21,0	–16,4	–16,1	–18,6
T9	–15,9	–13,0	–13,5	–15,2	–14,4
T10	– 8,0	–12,1	–11,1	–14,4	–11,4
T11	–30,1	–51,1	–51,4	–46,4	–44,8
T12	–61,1	–65,1	–33,0	–60,6	–50,6

Table 6 : Crop factors for different irrigation systems and soil water regimes in an irrigation trial at trial at Robertson.

Irrigation System	Treatment	Season	Oct.	Nov.	Dec.	Jan.	Feb.	March	Seasonal Means
Micro-jets	T2	1978/79	0,38	0,55	0,58	0,55	0,47	–	0,51
		1979/80	0,21	0,50	0,49	0,52	0,53	0,51	0,46
		1980/81	0,40	0,58	0,51	–	–	–	–
		1981/82	0,20	0,39	0,39	0,52	0,61	0,62	0,46
		1982/83	0,24	0,30	0,45	0,45	0,35	0,46	0,38
		Mean	0,29	0,46	0,48	0,51	0,49	0,53	0,45
Micro-jets	T3	1978/79	0,35	0,50	0,45	0,53	0,44	–	0,45
		1979/80	0,27	0,46	0,50	0,45	0,47	0,46	0,44
		1980/81	0,32	0,47	0,50	0,51	–	–	–
		1981/82	0,24	0,41	0,53	0,44	0,49	0,49	0,43
		1982/83	0,39	0,49	0,50	0,48	0,51	0,42	0,47
		Mean	0,31	0,47	0,50	0,48	0,48	0,46	0,45
Micro-jets	T4	1978/79	0,30	0,50	0,50	0,49	0,47	–	0,45
		1979/80	0,17	0,34	0,44	0,42	0,53	0,56	0,41
		1980/81	0,35	0,62	0,48	0,52	–	–	–
		1981/82	0,29	0,40	0,32	0,43	0,41	0,34	0,37
		1982/83	0,25	0,31	0,49	0,59	0,44	0,39	0,41
		Mean	0,27	0,43	0,45	0,49	0,46	0,43	0,42

Table 6 :   (Continued)

Irrigation System	Treatment	Season	Oct.	Nov.	Dec.	Jan.	Feb.	March	Seasonal Means
Tricklers	T10	1978/79	0,10	0,57	0,32	0,29	0,41	–	0,34
		1979/80	0,15	0,28	0,41	0,40	0,44	0,43	0,36
		1980/81	0,16	0,40	0,30	0,24	–	–	–
		1981/82	0,12	0,23	0,28	0,29	0,24	0,27	0,24
		1982/83	0,11	0,31	0,30	0,22	0,25	0,25	0,24
		Mean	0,13	0,36	0,32	0,29	0,34	0,32	0,29
Sprinklers	T11	1978/79	0,28	0,42	0,53	0,47	0,60	–	0,46
		1979/80	0,35	0,46	0,47	0,49	0,52	0,54	0,47
		1980/81	0,30	0,44	0,46	0,47	–	–	–
		1981/82	0,30	0,41	0,42	0,48	0,47	0,57	0,44
		1982/83	0,31	0,45	0,60	0,44	0,52	0,45	0,46
		Mean	0,30	0,44	0,50	0,47	0,53	0,52	0,45
Flood	T12	1978/79	0,37	0,42	0,49	0,75	0,71	–	0,55
		1979/80	0,28	0,35	0,43	0,42	0,45	0,43	0,39
		1980/81	0,32	0,41	0,30	–	–	–	–
		1981/82	0,22	0,22	0,34	0,37	0,48	0,44	0,35
		1982/83	0,20	0,39	0,36	0,53	0,43	0,49	0,40
		Mean	0,28	0,36	0,38	0,52	0,52	0,45	0,41
D-Value ($P \leq 0,05$) For Treatment Means			0,11	NS	0,11	0,15	NS	–	0,05

NS –   Not Significant
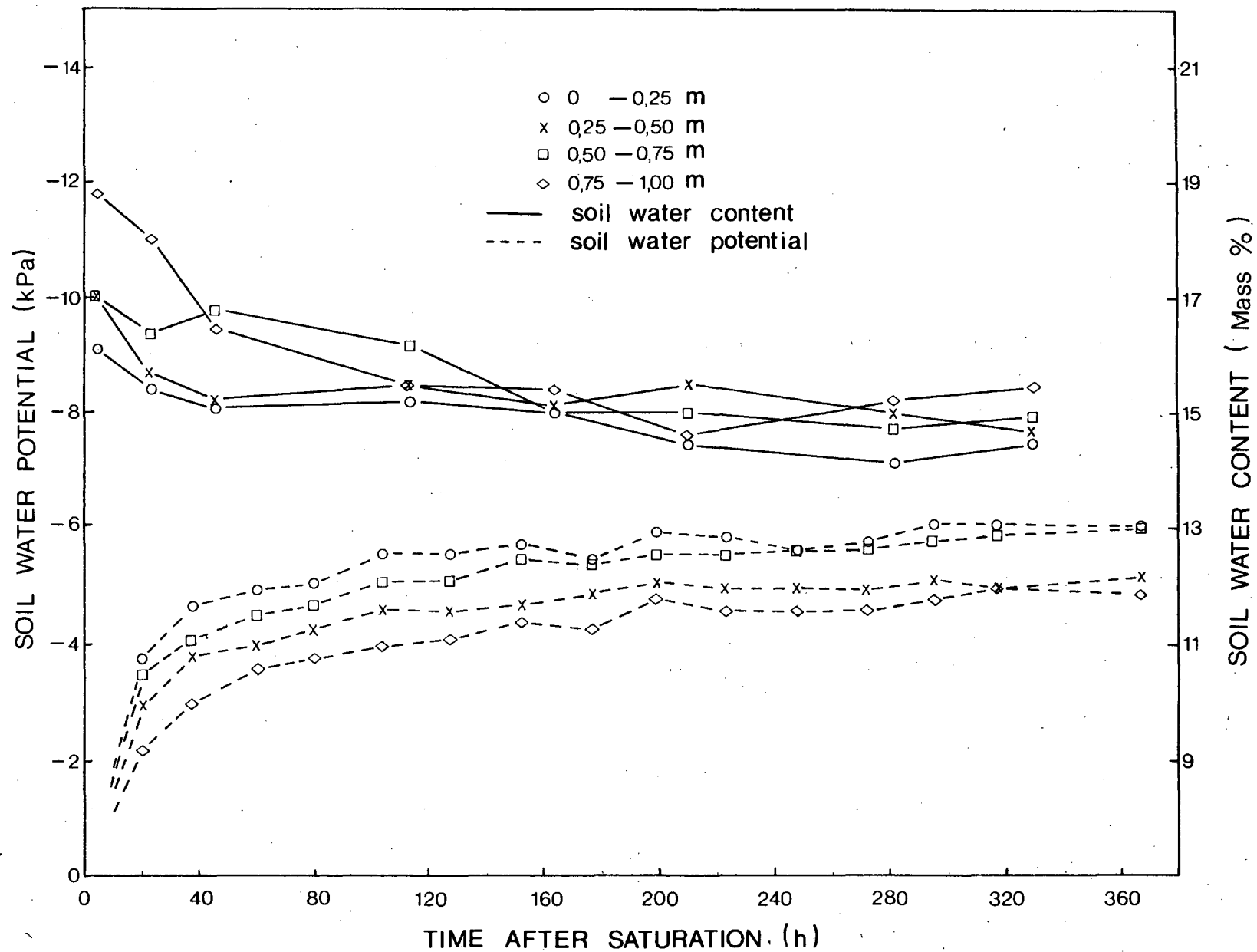
Fig. 1: Change in soil water status after saturation.
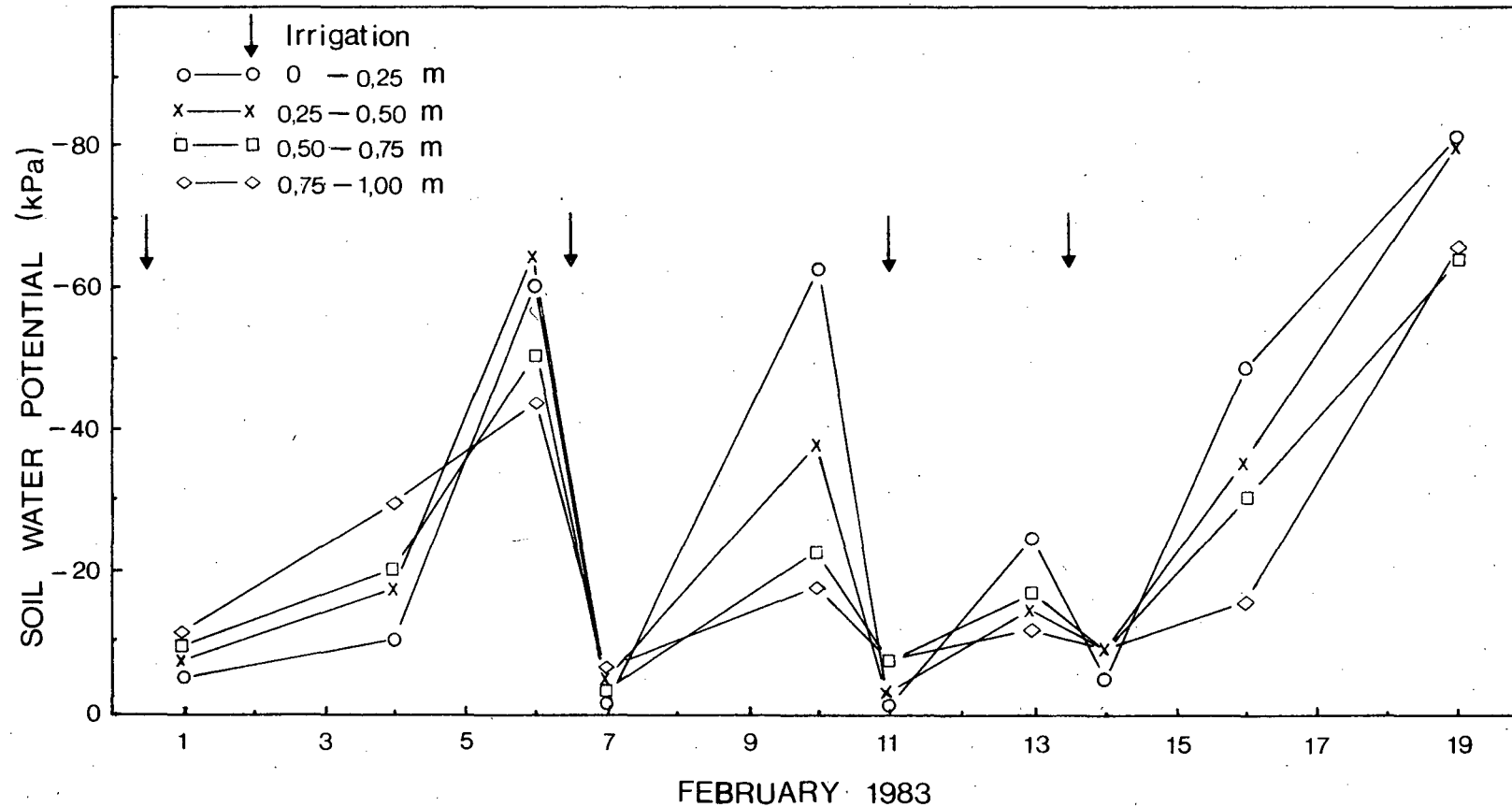
Fig. 2:   Rapid decrease in soil water potential on trickler plots due to the small reservoir of
available water.
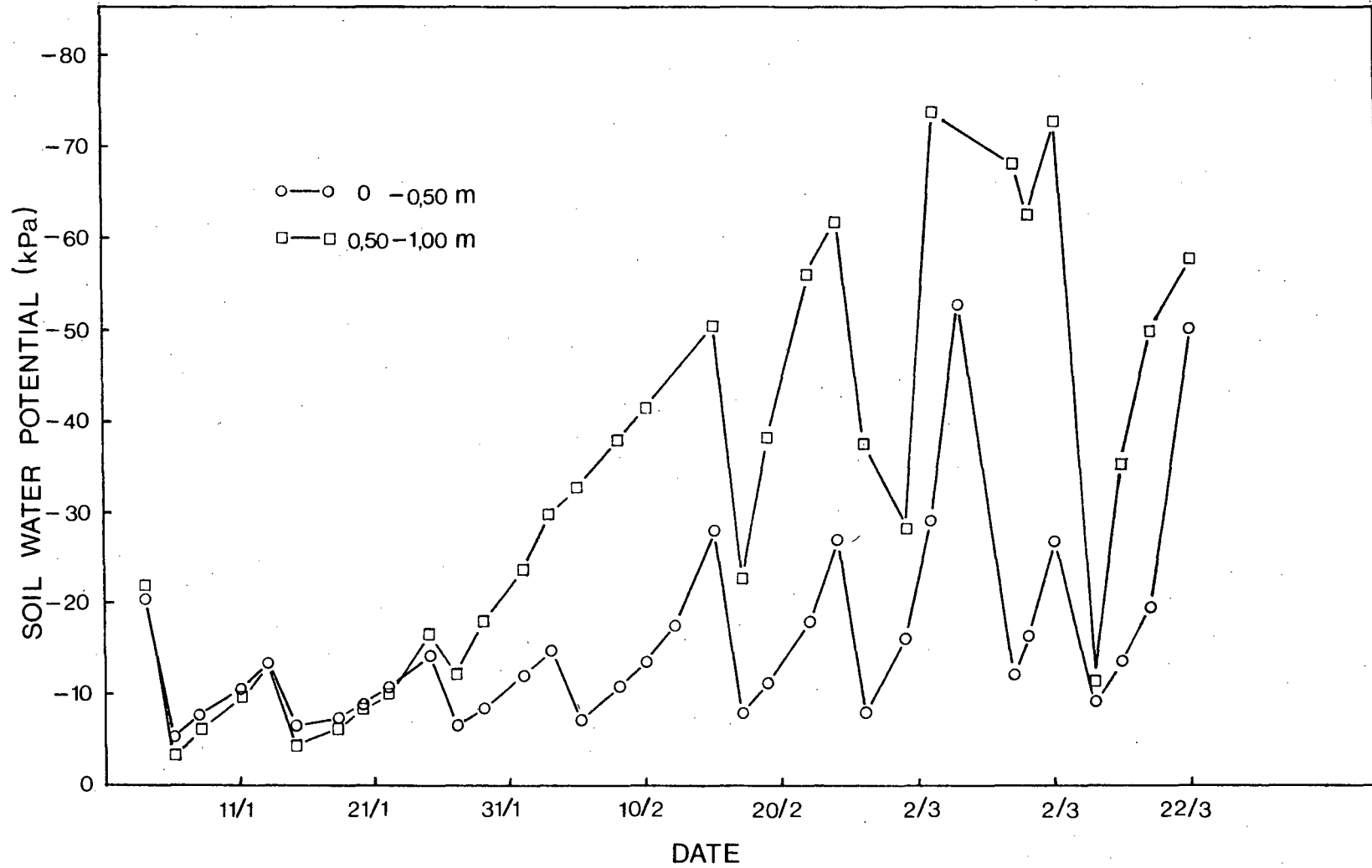
Fig. 3: Fluctuation in soil water potential of T9 plots during ripening of the grapes in the 1981/82 season.

LATERAL   DISTANCE   (m)   FROM   TRICKLER
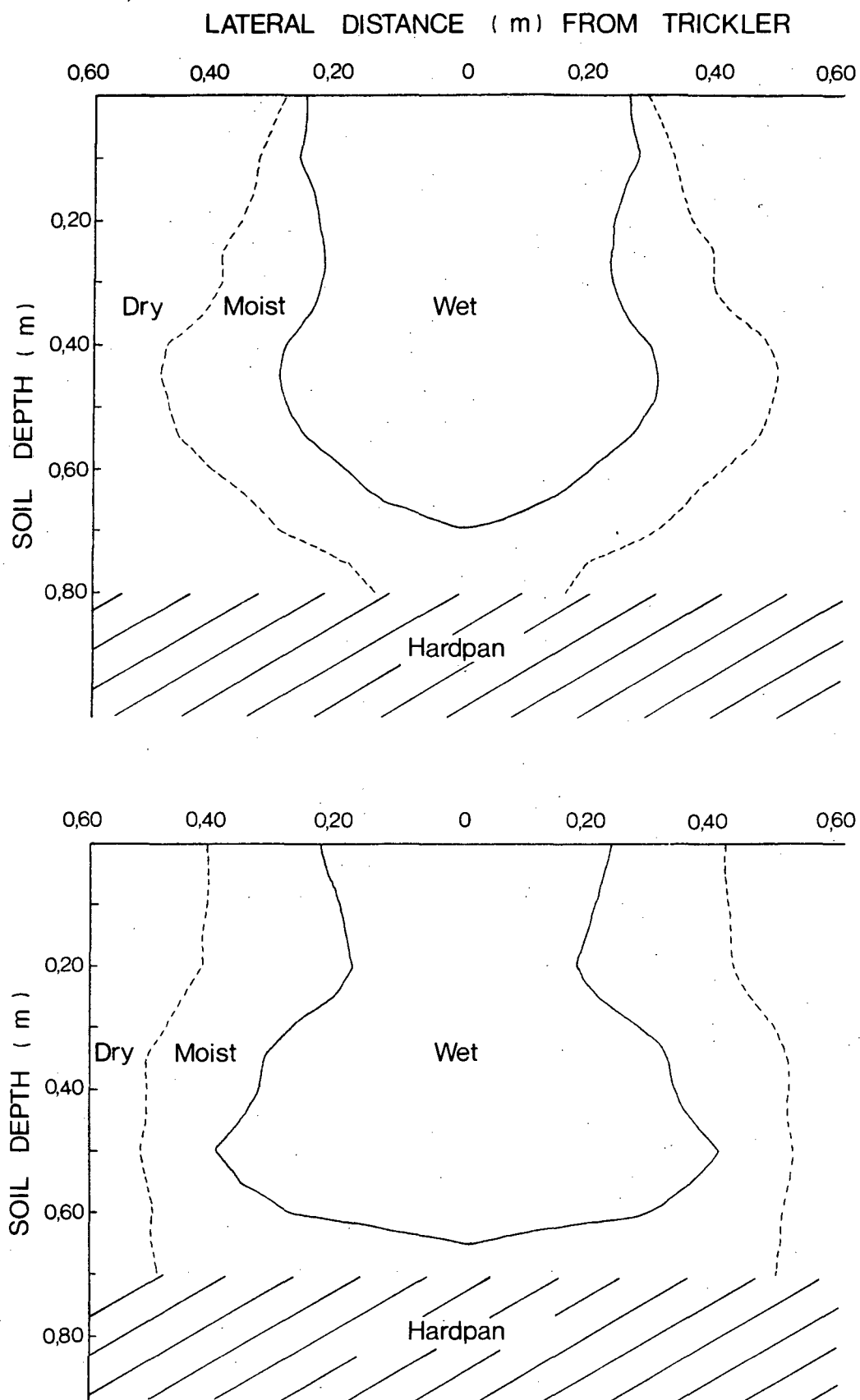
Fig. 4: Wetting patterns under tricklers on two representative
sites as mapped visually from profile walls.
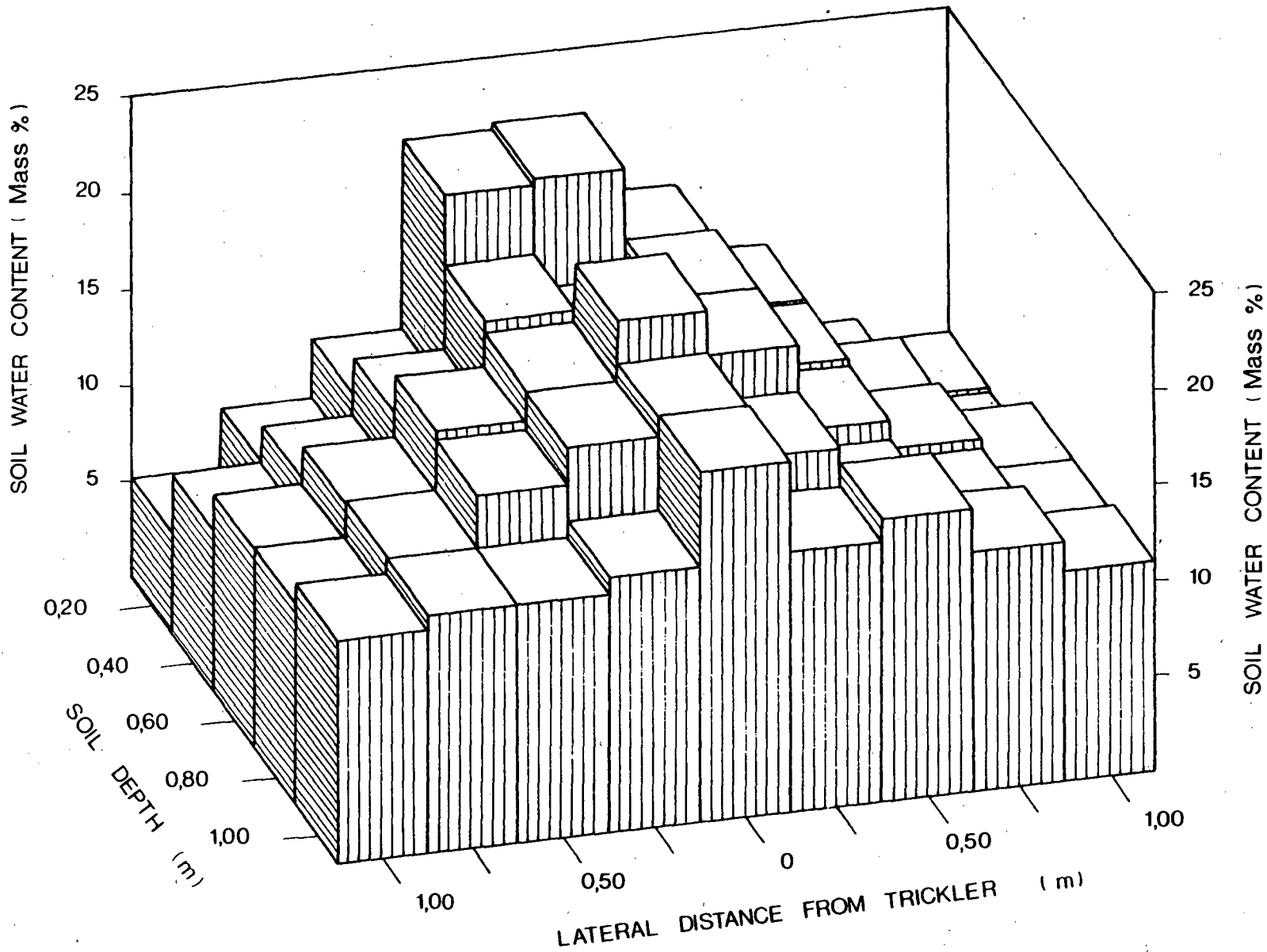
Fig. 5. Mean soil water distribution determined gravimetrically under tricklers at representative
positions on five plots in the irrigation trial.
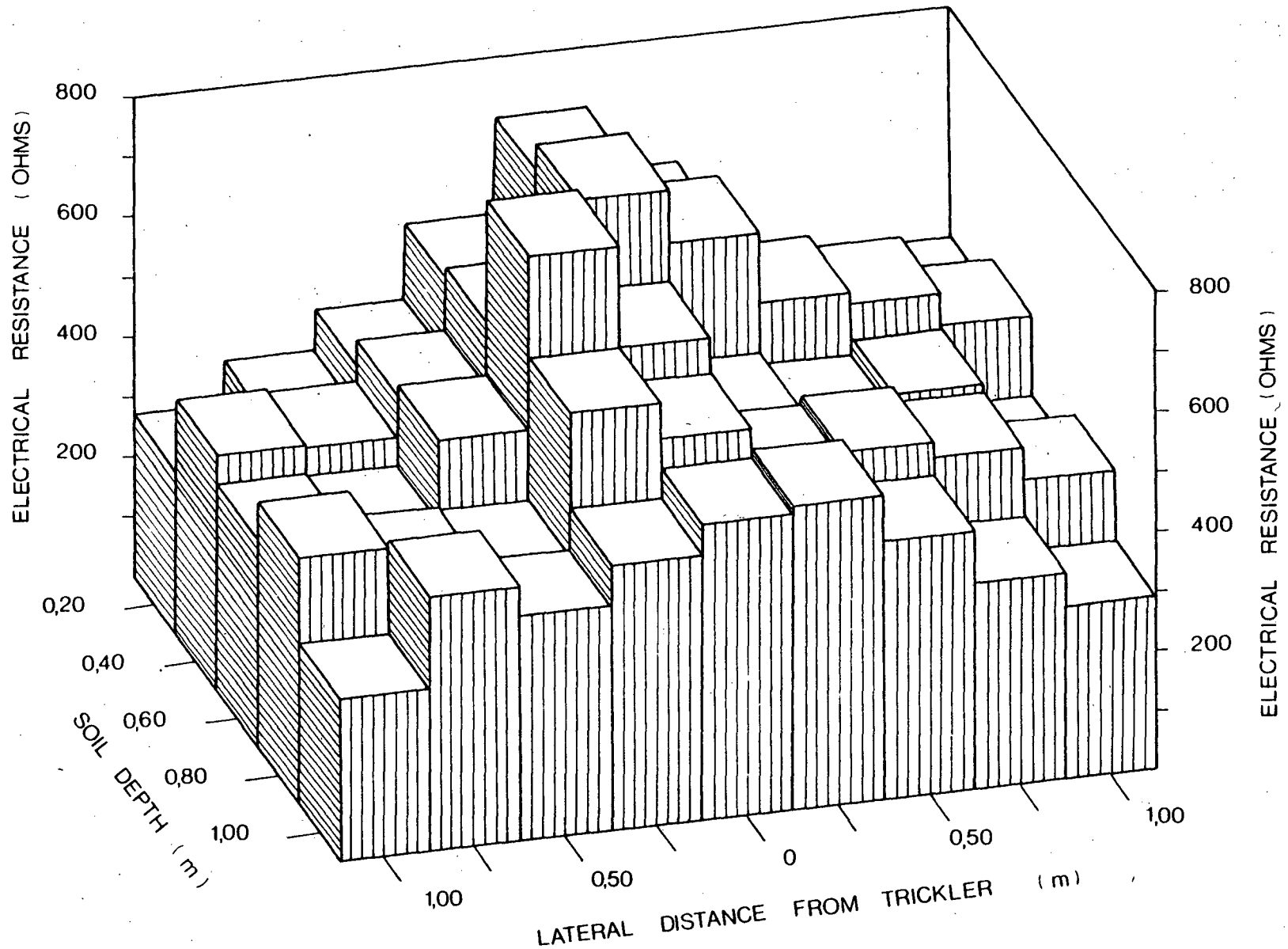
Fig. 6: Mean salt distribution as indicated by electrical resistance under tricklers
at representative positions on five plots in the irrigation trial.
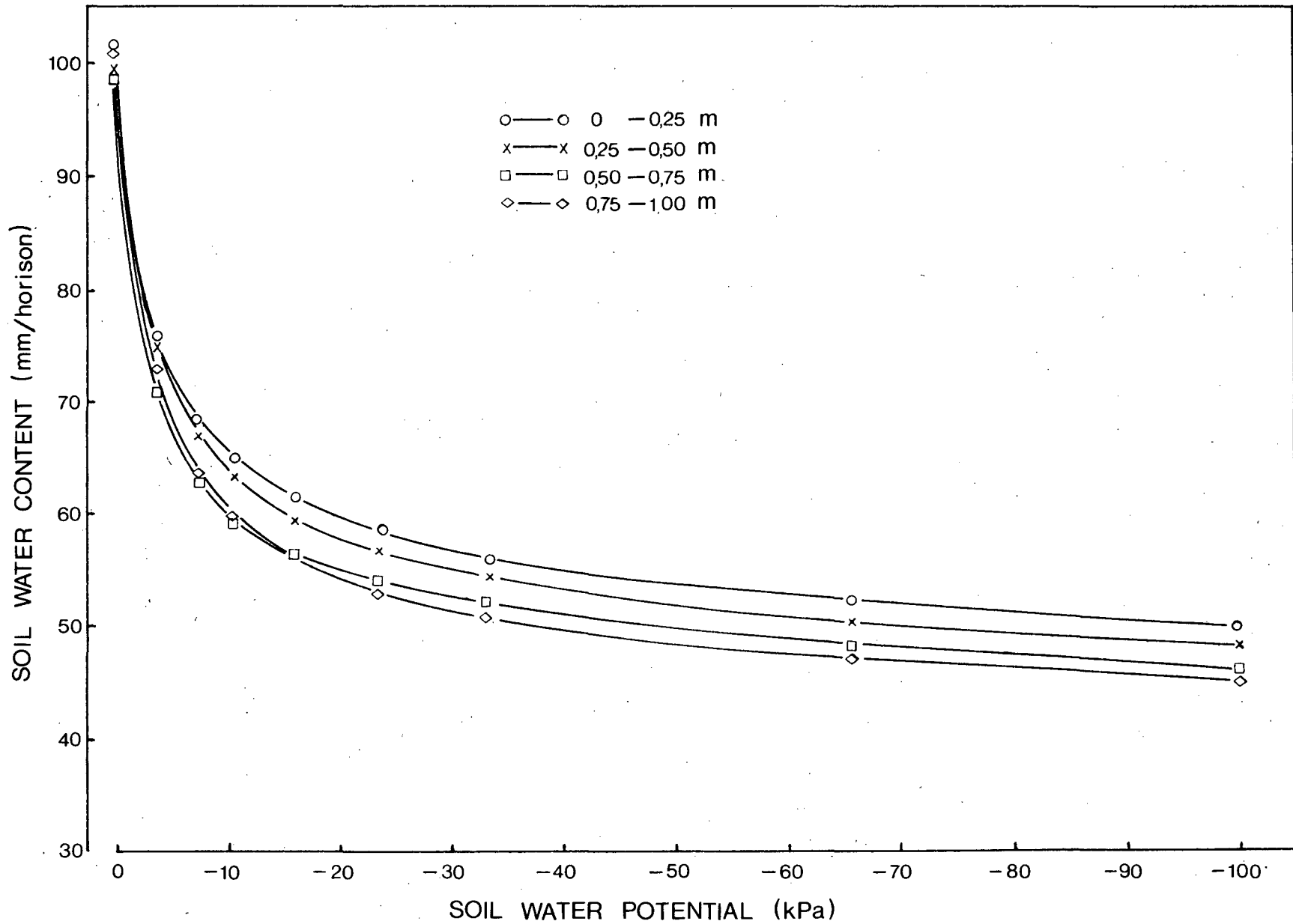
Fig. 7: Soil water retention curves for the conversion of tensiometer readings to soil water content.
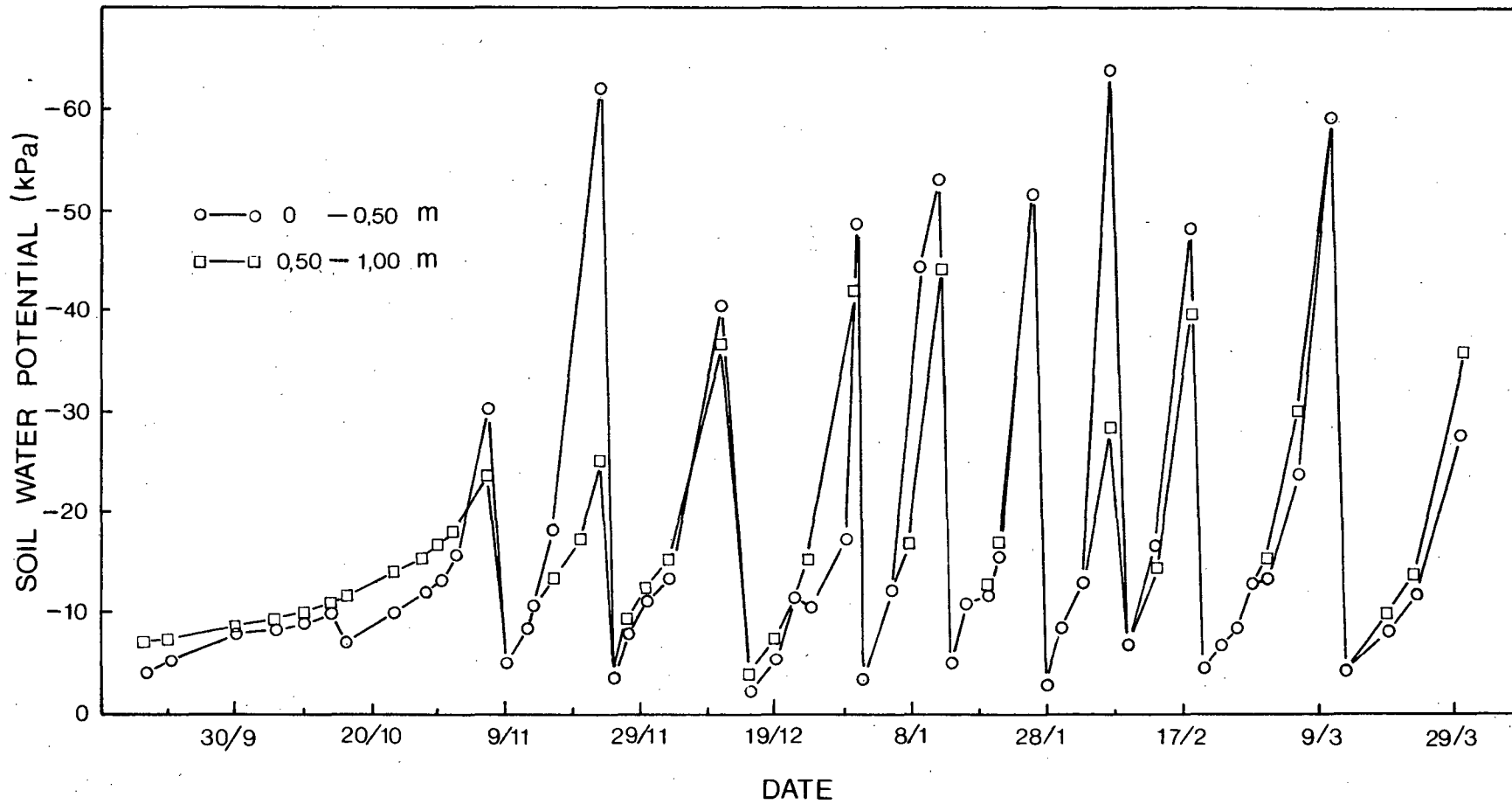
Fig. 8:   Variation in soil water potential as indicated by tensiometers on T2 plots   (50 % soil water regime).
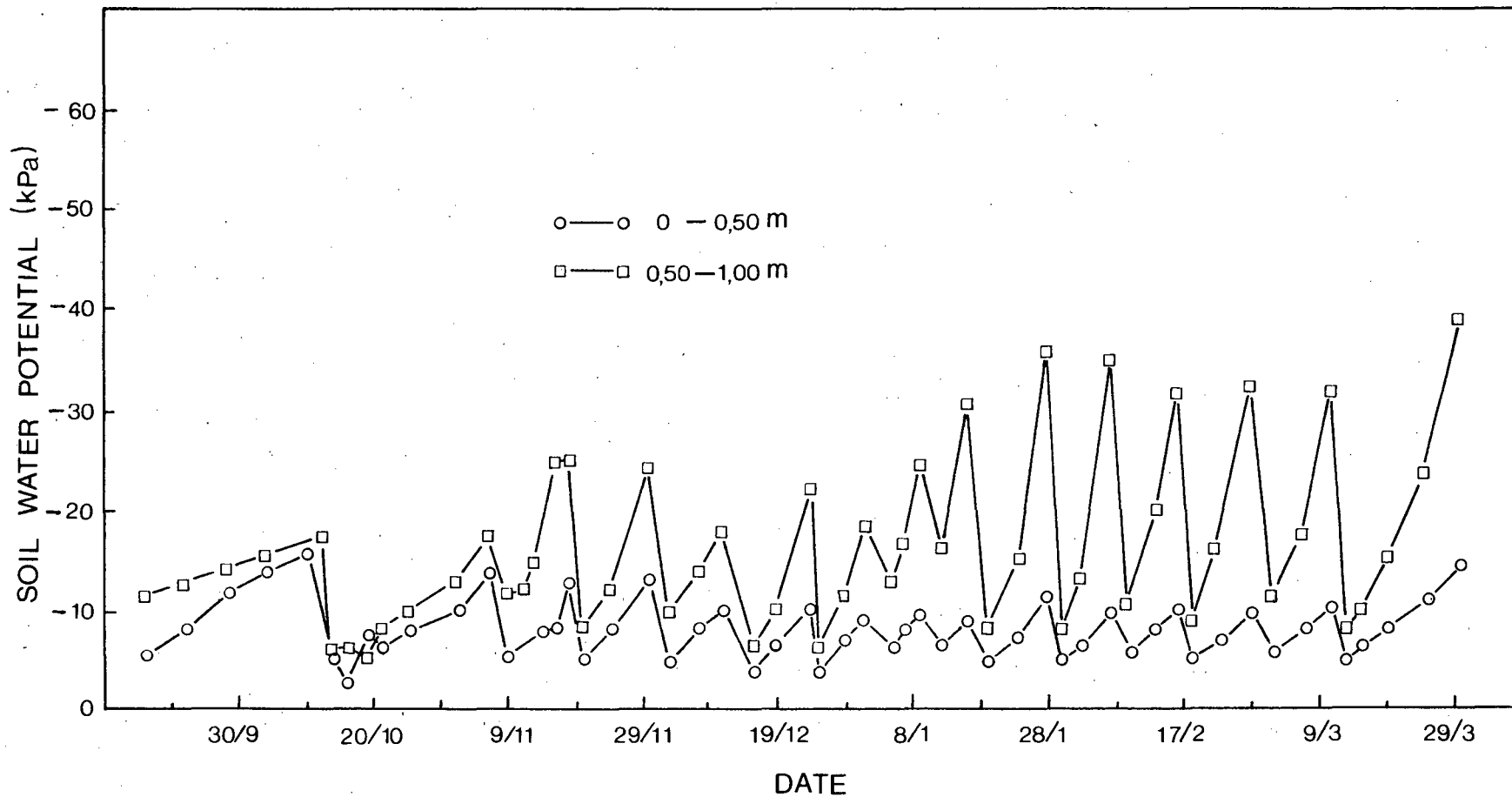
Fig. 9: Variation in soil water potential as indicated by tensiometers on T3 plots   (70 % soil water regime).
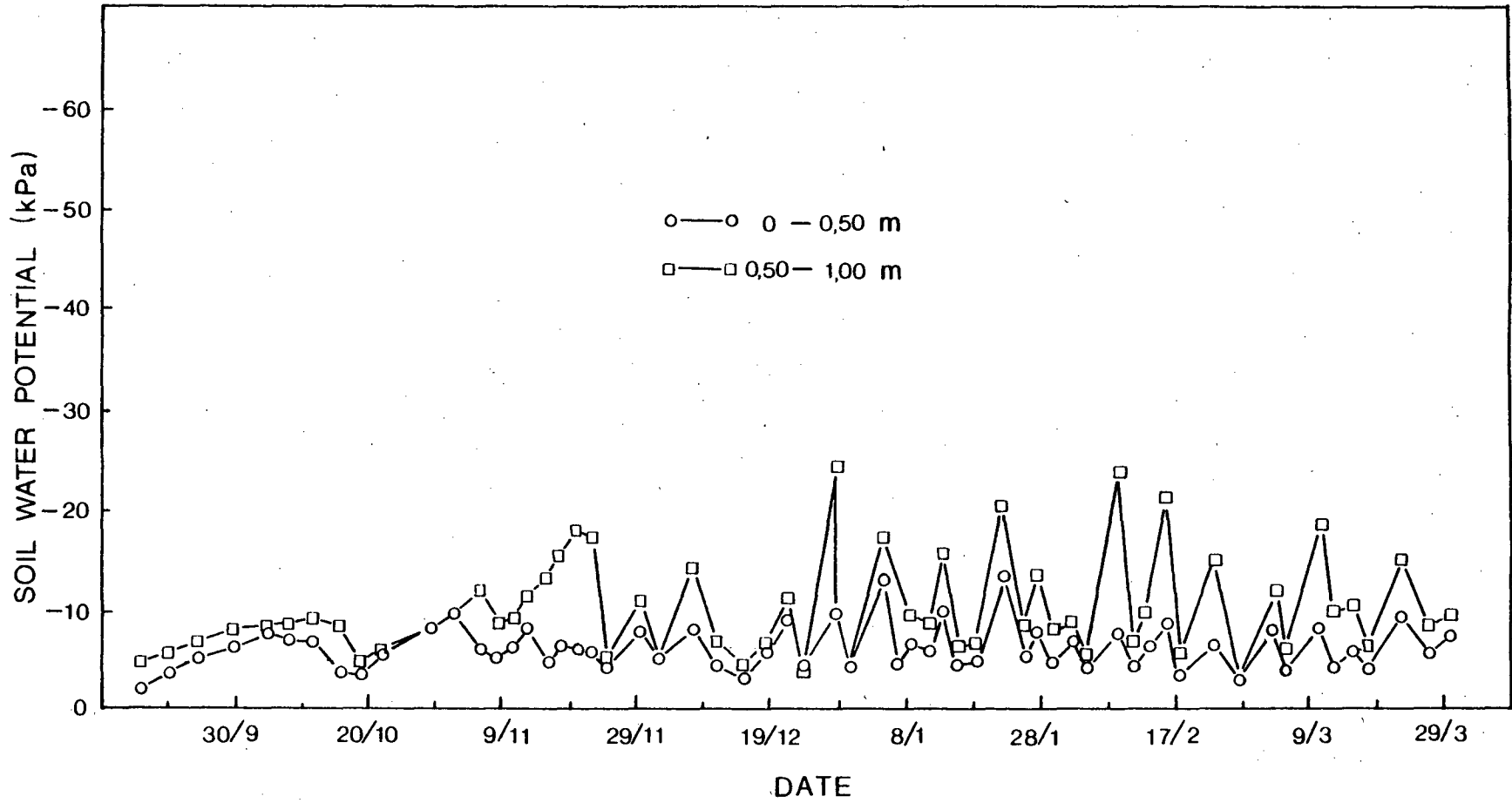
Fig. 10:   Variation in soil water potential as indicated by tensiometers on T4 plots   (90 % soil water regime).
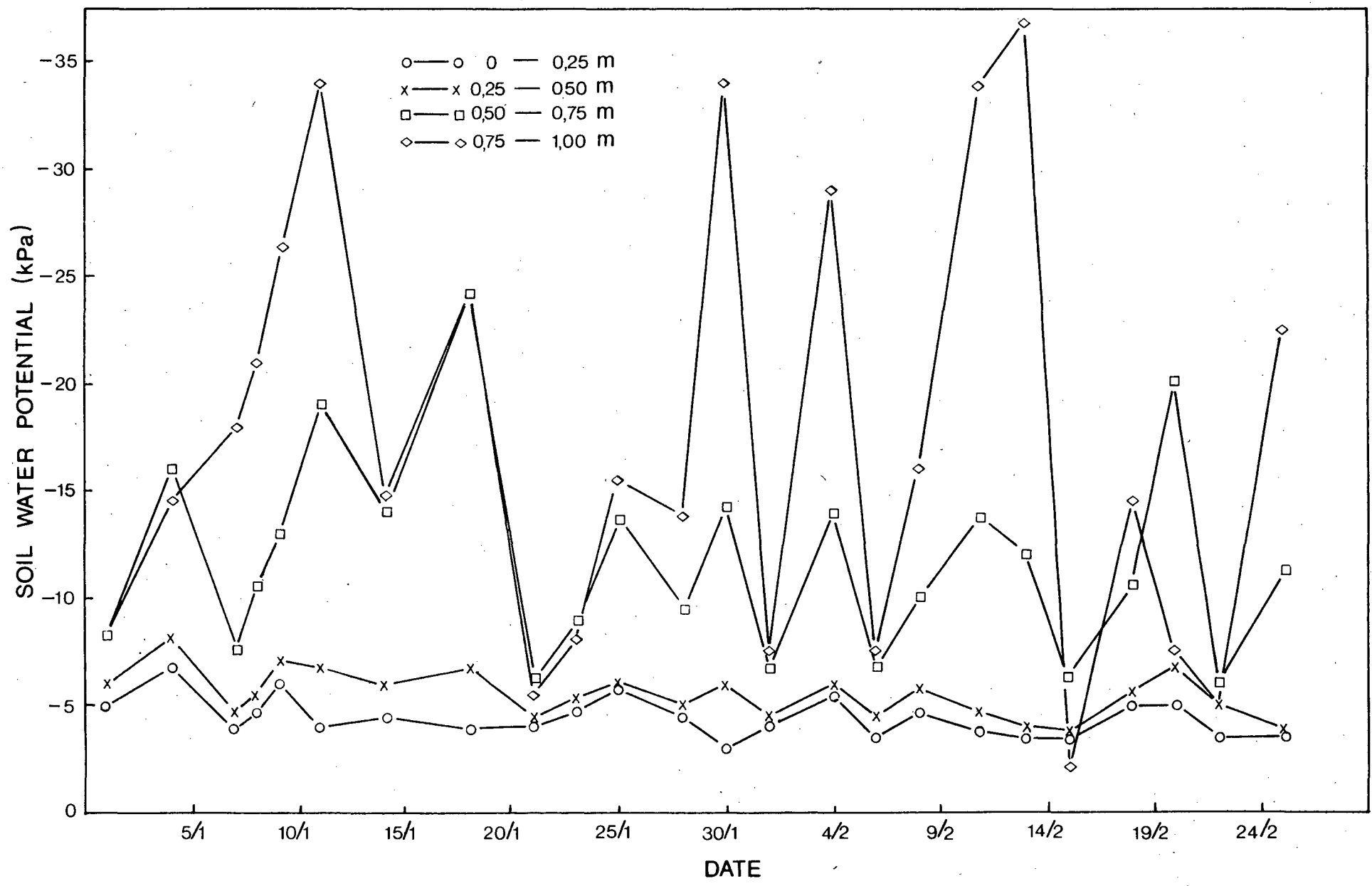
Fig. 11: Variation in soil water potential at different depths on a treatment plot maintained at a 90 % soil water regime during two months of peak water consumption.
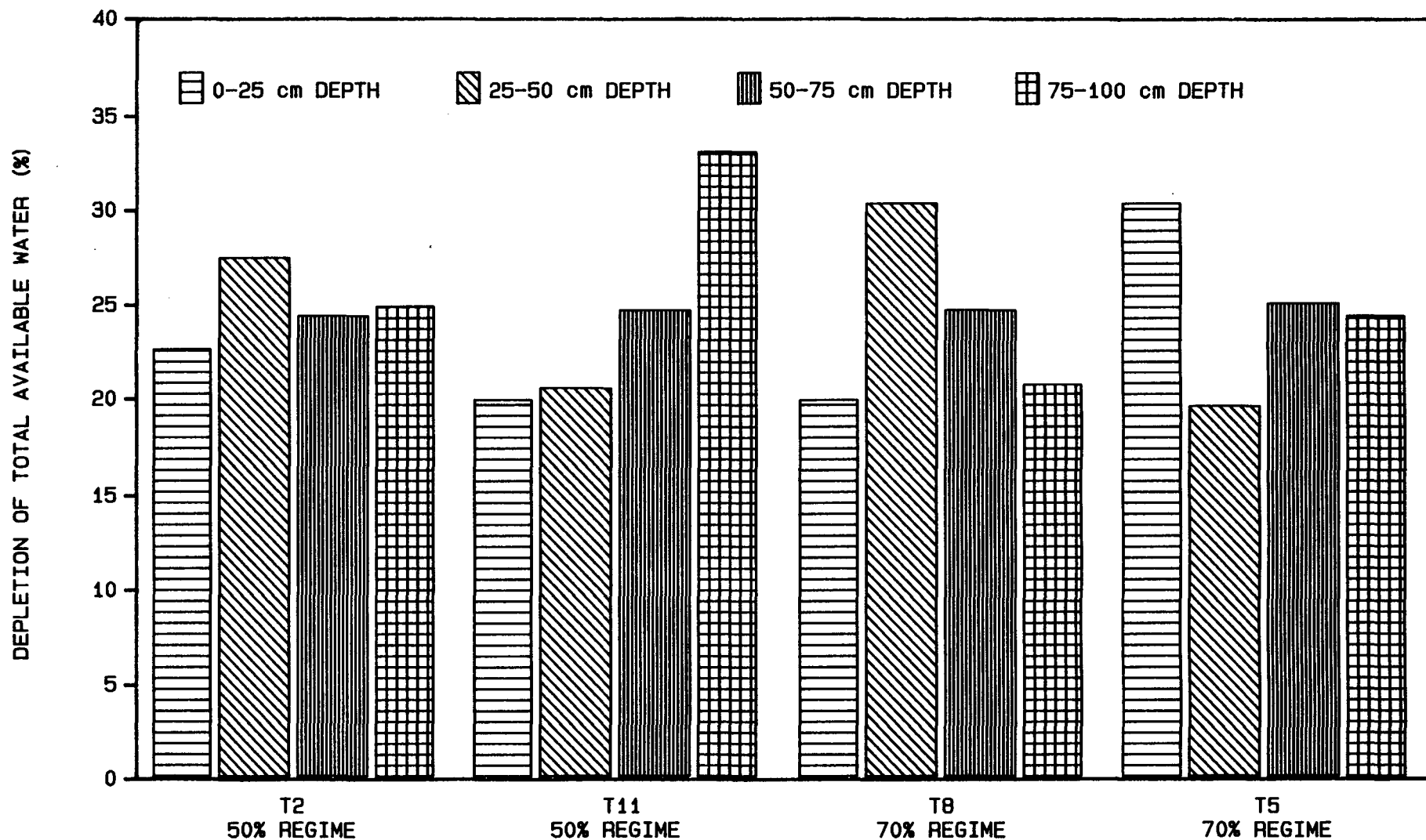
Fig. 12:   Average soil water depletion with depth of four irrigation treatments representative of similar
treatments in an irrigation trial with Colombar/99R during the period 1978/79 – 1982/83.

CHAPTER 6

DIURNAL VARIATION IN VINE WATER STRESS AS A FUNCTION OF CHANGING SOIL WATER STATUS AND METEREOLOGICAL CONDITIONS

INTRODUCTION

The soil-water-plant-atmosphere continuum can be described as a stream flowing from a source of limited capacity and variable potential namely the soil reservoir, to a sink of unlimited capacity and of variable potential, the atmosphere (Hillel, 1971). Many variables affect this complicated continuum, necessitating a wide and comprehensive research approach when plant water relations are studied.

Transient plant water deficits develop during the day due to water losses which exceed water uptake. Water stress of longer duration as a result of decreasing soil water content is of greater importance to viticulture. Such long term deficits commence, as described above, but as the soil water potential gradually decreases, plants are eventually unable to recover at night. Therefore the soil water potential sets the level of recovery at night (Slatyer, 1967; Begg & Turner, 1976). Each plant organ and physiological process may respond differently to increasing water stress. Hsiao (1973) acknowledged this fact and listed plant parameters in sequence of decreasing sensitivity.

Morphological responses to water stress are often associated with the response of more sensitive underlying physiological processes (Oosterhuis, 1982). Consequently a study of plant water stress should include a variety of the more promising of these physiological parameters in addition to more conventional morphological indicators. Water potential has gained wide

acceptance as a fundamental measure of plant water status (Kramer, 1983), and has been applied in viticultural research (Smart & Coombe, 1983). Pre-dawn water potential approaches equilibrium with soil water potential and reaches a maximum daily value (Smart & Coombe, 1983). In using water potential reduction as a indicator of water stress, an absence of osmotic adjustment to the stress is assumed (Hsiao et al., 1976).

Stomatal opening is affected by water deficits and can be used as an indicator of plant water stress, although it is recognized that environmental factors such as light, CO_2 and temperature also affect stomatal behaviour (Kramer, 1983). Stomatal opening, transpiration and phytosynthesis often decrease concommitantly in plants subjected to increasing water stress. However, there is evidence that water stress not only results in a decline in CO_2 uptake via closure of stomata, but can cause inhibition of CO_2 fixation (Kramer, 1983). Photosynthetic rate reaches a maximum at low water stress, declines with increasing stress and recovers on rewatering (Hofäcker, 1977; Smart & Coombe, 1983).

Against the above background, an investigation was conducted to determine (a) the onset of vine water stress using some physiological plant parameters and (b) to establish their interrelationships and the interaction with environmental conditions both during diurnal cycles as well as during soil drying over the longer term.

MATERIALS AND METHODS

Experimental Layout

The investigation was conducted in an irrigation trial with Vitis vinifera cv. Colombar grafted on 99R rootstock in the Breede River valley.

This trial comprised recharging of soil water from specified levels to field water capacity (FC), water stress applied at different phenological stages as well as the few major irrigation systems used in viticulture (see detailed description of irrigation treatments in previous chapters). Soil water content (SWC) and soil water potential (SWP) were monitored regularly every two days at four depths on the different treatment plots. Mean water content and water potentials for the four soil depths were used in the statistical analysis of relationships among the measured parameters. A standard weather station close by, supplied metereological data.

During the phenological stage of ripening which generally commenced in middle January and ended with harvesting at the end of March for the experimental vineyard, several plant parameters of water stress were determined on vines of three of the 12 treatment plots. This series of measurements started on 14/1/82, two days after the soil water of the selected treatment plots was replenished to FC by irrigation and continued until 24/3/82 (a day before harvesting). The three treatments represented three soil water regimes viz.:

* T4 - 90% soil water regime ("wet" treatment)

* T8 - 25% soil water regime during the ripening stage ("dry" treatment).
     Plots belonging to this treatment were irrigated on 12/1/82 and only
     on 12/3/82 thereafter, 13 days before harvesting

* T9 - Weekly irrigations to maintain a 70% soil water regime in the
     0 - 0,50 m soil depth. The subsoil (0,50 - 1,0 m) was allowed to
     dry out.

Prior to the main investigation conducted during the 1982 ripening stage, a study of the water potential of sunlit leaves, shaded leaves and bunches were carried out in the same vineyard during the ripening stage. Two treatments namely T4 (90% regime) and T1 (25% regime) were included in this investigation which was carried out on four days during two seasons with the aim of determining the diurnal fluctuation of water potential in the leaves and fruit.

Measurements

Five test vines per treatment were selected visually and fully matured leaves on the upper third of fruit bearing shoots were used. Measurements were concentrated on fully sunlit leaves, although shaded leaves were also included on T4 and T8 plots for the purpose of comparing leaf positions.

Measurement dates were as follows :   14/1/82, 20/1/82, 28/1/82, 4/2/82, 16/2/82, 8/3/82 and 24/3/82. Each of these days started with the determination of pre-dawn leaf water potentials (LWP_p) in a Scholander pressure chamber (Scholander et al., 1965). Thereafter sets of determinations were carried out five times during the course of the day viz., at approximately 08h00, 10h00, 12h00, 14h00 and 17h00. Preliminary studies in the same vineyard, prior to this investigation, proved these times adequate to give a representative picture of diurnal changes in the plant parameters under discussion. Each set of determinations required a team approach in order to complete measurements in as short a time as possible - less than 45 minutes was usually needed - and thus minimize the effect of changing environmental conditions. After selection of a representative leaf, stomatal resistance (Rs) was measured with an automatic diffusion porometer. Leaf temperature was recorded simultaneously by a thermistor installed in the sensor head of the porometer. Photosynthetic active radiation (PAR) was determined with a

portable radiometer by holding a quantum sensor above the leaf blade and at the same angle as the leaf blade relative to the sun. Following measurements of PAR, total photosynthetic activity was determined on the same leaf using the method of Shimshi (1969). This method comprised the following : Radioactively labelled CO_2 was allowed to flow for 20 seconds over both sides of a small leaf area (ca. 100 mm^2) enclosed by a small chamber. Upon removal of the chamber, a leaf disc of known size (78,5 mm^2) was immediately punched out, and put into a small vial which was then placed in liquid N to stop all respiration processes. The leaf discs were taken to the laboratory, ashed and the radio-activity determined in a liquid scintillation counter. Based upon the difference in uptake rate between $^{14}CO_2$ and $^{12}CO_2$ (Van Norman & Brown, 1952), a correction factor, dependent on the activity used in this experiment, was calculated to obtain the actual uptake of CO_2 (Austin & Langdon, 1967). CO_2 uptake was calculated as follows :

$$CO_2 \text{ uptake } = 12,003 \ \frac{y^1}{y} \ \text{mg } CO_2 \ dm^{-2}h^{-1} \text{ where,}$$

where,

y^1 = radio-active count of sample

y = radio-active count of standard

The final determination in the series of measurements on the same leaf, required removal of the leaf for the LWP reading. Each measurement day comprised a total of 75 determinations for every plant parameter on sunlit leaves as well as a further 30 determinations on shaded leaves.

Data Processing

A standard two-way analysis of variance was applied to the data sets in

order to compare water regime treatments with regard to the different plant parameters. Additionally a stepwise regression programme (BMDP/2R) was applied to determine simple correlation coefficients (r), multiple correlation coefficients (R) and the coefficient of determination (R^2) as well as regression equations in order to quantify relations among soil water status, metereological factors and plant parameters of water stress. Data depicting diurnal variation were separated from those demonstrating changes over the longer term (January to March). In the latter case only data at the time of maximum stress during the day i.e. between 14h00 - 15h00 were used. However, LWP_p was also included, because this parameter is generally not much affected by climatological conditions and should in theory only reflect soil water status.

To explain diurnal changes in plant parameters, the following variables were used as input :

X_1 = Relative Humidity   = RH (%)

X_2 = Wind Speed   = Wind (km h^{-1})

X_3 = Photosynthetic Active Radiation = PAR ($\mu Em^{-2}s^{-1}$)

X_4 = Leaf Temperature   = Tl (°C)

X_5 = Leaf Water Potential   = LWP (kPa)

X_6 = Stomatal Resistance   = Rs (s cm^{-1})

Variables used as input to determine relationships during the drying cycle of treatment T8 were as follows :

X_1 = Soil Water Content   (mass %)   = SWC (%)

X_2 = Soil Water Potential   (profile mean)   = SWP (kPa)

X_3 = Relative Humidity   (14h00)   = RH (%)

X_4 = Leaf Temperature   (14h00)   = Tl (°C)

X_5 = Leaf Water Potential (14h00) = LWP_{14} (kPa)

X_6 = Stomatal Resistance (14h00) = Rs (s cm $^{-1}$)

X_7 = Pre-dawn Leaf Water Potential = LWP_p (kPa)

RESULTS AND DISCUSSION

Diurnal Patterns

All plant parameters of water stress measured during the investigation displayed a diurnal variation. The daily changes in water potential of sunlit leaves, shaded leaves and whole bunches for vines at a high soil water regime (T4 = 90% regime) are depicted in Fig. 1 and those for stressed vines (T1 = 25% regime) in Fig. 2. These diurnal patterns, typical of vine water potentials determined on other days and in other seasons as well, clearly showed that the water potential of sunlit leaves was significantly lower than that of shaded leaves during the middle part of the day (10h00 - 16h00). This fact was further illustrated by comparing sunlit and shaded leaves in the drying cycle experiment, yielding an average LWP of -1282 kPa for sunlit leaves and -1026 kPa for shaded leaves (D-value = -51 kPa) during day time.

The water potential of bunches was lower than that of leaves during the pre-dawn period (Fig. 1 & 2). However, LWP, especially that of sunlit leaves, decreased much more rapidly in the morning and also increased at a faster rate in the afternoon than bunch water potential. Bunches always reached their minimum water potential later in the day than the leaves. It was also noticable that LWP_p, assumed to be in equilibrium with the soil water potential, was always, even on wet control plots such as T4 (Fig. 1), lower than the water potential in the soil (SWP = -5 kPa compared to LWP_p = -80 kPa on T4 on 6/1/82).

The difference in response rate between leaves and bunches can probably be ascribed to different water capacities. Due to its smaller capacity, small losses of water in a leaf should lead to larger changes in water potential. The loss of similar quantities of water should result in smaller changes in water potential in the bunches which have a much greater water capacity. The delayed decrease in water potential may also be due to an indirect pathway of water loss from the berries which are known to contain no stomata (Pratt, 1971). From the diurnal water potential changes in Fig. 1 & 2 it is clear that a water potential gradient existed from approximately 08h00 to 16h00 between sunlit leaves and the bunches. Water would consequently flow from the bunches to the sunlit leaves (Fig. 3). This driving force would not only lead to water loss from the bunches but also from other plant organs such as trunks, known for their diurnal shrinking and swelling in phase with gains and losses of water in the plant (Kozlowski, 1972). Depending on plant resistances to redistribution of water in the plant (not determined in this study), bunches would thus lose water via sunlit leaves. This mechanism could explain the delayed decrease of bunch water potential.

Recharging of plant water content takes place through root uptake. According to the above hypothesis, the bunches can be viewed as reservoirs which are filled by water extraction from the soil in the late afternoon and at night, and which supply water again to the leaves and other tissue during part of the day (Fig. 3). If true, the mechanism could explain to some extent why heavily cropped vines require more water than ones bearing less fruit. This latter phenomenon is well-known among farmers and was actually proved by soil sampling in the experimental vineyard (Table 1). In this comparative study the consumptive water use (67,2 mm) of vines with a crop load of 17,74 kg was significantly more than the water use (52,9 mm) of vines which bore only 8,97 kg of grapes during a 27 day period in summer. However, the effect of crop load on plant water requirements is normally

explained by lower stomatal resistances in fruiting plants compared to non-fruiting plants (Hofäcker, 1976; Monelise & Lenz, 1980). Loveys & Kriedemann (1974) suggested that stomatal response is hormonally controlled in vines.

For the ease of interpretation results of one typical measurement day (4/2/82) are presented in Figs. 4, 5, 6, 7 & 8. Photosynthetic active radiation increased from the morning reading to a maximum of 1366 μE m^{-2}s^{-1} during the middle part of the day, after which it decreased again (Fig. 4). The relative humidity followed the inverse pattern with a minimum of 19% between at 15h00 (Fig. 5). Wind speed increased from 6 km h^{-1} to a maximum of 21 km h^{-1} and leaf temperature from 23°C to 34°C (Fig. 5). These patterns were typical of measurement days although the magnitude of the parameter values differed somewhat from day to day.

At this stage in the drying cycle (4/2/82) the pre-dawn LWP of T8 (stressed plot) was already -200 kPa below that of both T4 and T9 vines (Fig. 6). This difference in LWP between T8 and the other two treatments due to water stress in the T8 vines, continued throughout the day, and was reflected in the water potentials of both sunlit and shaded leaves. The higher LWP of shaded leaves in comparison with its sunlit counterparts is once more clearly illustrated in Fig. 6. Measurements of LWP showed no signs of water stress in T9 vines.

On this measurement day LWP was correlated significantly with Tl (r = -0,95), PAR (r = -0,85), RH (r = 0,82) and even with wind (r = -0,63) (Table 2). Stepwise regression analysis showed that leaf temperature could explain 90% of the variation in LWP on 4/2/82 (Table 3). Of all the variables, leaf temperature correlated best with LWP on most measurement days yielding a partial correlation coefficient (R) = -0,90 on average. Relative humidity correlated best with LWP on 20/1/82, 16/2/82 and 24/3/82 of which the first

two days were cooler than normal and the RH remained fairly high even at 14h00.

Stomatal resistance explained a further 9%, 15% and 17% of the variation in LWP on 20/1/82 and 24/3/82 respectively (Table 3).

On the typical measurement day of 4/2/82, Rs for sunlit leaves decreased from the first reading of the day to assume low values (between 1,5 and 3,0 s cm $^{-1}$) during the middle part of the day and increased again in the late afternoon (17h00 - 18h00) for the two unstressed treatments T4 and T9 (Fig. 7). Stomata of T8 vines were already partly closed during the middle part of the day as could be seen from the significantly higher Rs values of this treatment in comparison with T4 and T9. Stomatal resistances of shaded leaves were always much higher than those of sunlit leaves, probably due to the lower light conditions in their vicinity (Fig. 4). An analysis of Rs values pooled over all dates and times of the day yielded 10,97 s cm $^{-1}$ and 23,52 s cm $^{-1}$ (D-value = 10 s cm $^{-1}$) for sunlit and shaded leaves respectively. In general, stomatal resistance did not correlate well with the other measured parameters on individual days, the exception being 20/1/82 and 16/2/82 when PAR explained 45% and PAR + Tl explained 68% of the variation in Rs respectively (Table 3).

Photosynthetic activity for the stressed vines (T8) was significantly lower than for its unstressed counterparts (T4 and T9) between 10h00 and 15h00 on 4/2/82 (Fig. 8). Midday values for the unstressed vines varied between 70 and 83 mg CO_2 dm $^{-2}$h $^{-1}$. The results illustrated in Fig. 4, 5, 6 & 7 obviously suggested a dependency of PA on the other parameters. This relationship was quantified when the data was subjected to a stepwise regression analysis. On the typical day (4/2/82) PA was correlated best with PAR (r = 0,74) (Table 2). Significant correlations were also found

with all the other parameters except wind speed. Regression analysis showed that PAR could explain 50% of the variation in PA. An additional 14% could be explained by Rs (Table 3). When other measurement dates were also considered it became apparent that PAR was the predominant factor which controlled photosynthesis on most dates and could explain on average (8/3/82 excluded) 43% of the variation in this plant parameter. On 8/3/82 when T8 had already been stressed severely, photosynthesis was best correlated with Rs (R = -0,71).

Onset of Vine Water Stress

In order to eliminate the diurnal variation in the plant parameters of water stress and the climatological conditions as far as possible, and to assess the effect of soil water status on plant parameters, all measured values for T8 and T9 were compared to those of T4 (control). The diurnal curves suggested that differences were largest during the time of maximum stress i.e. 14h00 - 15h00. Consequently differences between treatments and control at that time of day were plotted against time in order to determine the onset of vine water stress (Fig. 9).

Treatment 9, which allowed soil water replenishment in the upper half of the soil profile only, at no stage showed a significant deviation from the control values as regards Rs or PA (Fig. 9). Pre-dawn LWP surpassed the control values from 28/1/82, and LWP_{14} did so on two dates (4/2/82 and 24/3/82) only. It therefore appeared as if T9 vines experienced very little stress despite a low water potential in part of its root zone.

T8 vines responded to the drying of the soil as regards the four plant parameter differentials (Fig. 9). The pre-dawn LWP differentials (ΔLWP_p), obtained by subtracting control values from test values, became significant

for the first time on 28/1/82 (Fig. 9a). Onset of stress, as indicated by LWP_p thus occurred between 20/1/82 and 28/1/82 and the stress continued till the end of the season.

Pre-dawn LWP was correlated significantly with SWC (r = 0,89) and SWP (r = 0,95) (Table 4). The latter variable, being a fundamental property and in its effect independent of soil type, was in the present study preferred to SWC as an independent variable for regression analysis. Soil Water Potential explained 90% of the variation in LWP_p. Substitution of Y by LWP_p (-316 kPa at the detection of water stress) in the regression equation (Y = -98,6541 + 3,3840 X_2) obtained through stepwise regression analysis, indicated the onset of water stress at a SWP of -64,2 kPa. The SWP value corresponded to a soil water regime of 42%.

Leaf water potentials at 14h00 seemed to be a less sensitive indicator of vine water stress than the pre-dawn values. Differentials of LWP_{14} ($\triangle LWP_{14}$) started to increase on 28/1/82, but this increase only became significant on 4/2/82 (Fig. 9b). A number of soil, atmospheric and plant parameters correlated significantly with LWP_{14} (Table 5). The coefficient of determination (R^2 = 0,70) was highest for SWP. Addition of RH as a independent variable into the regression equation accounted for an additional 23% of the variation in LWP_{14}. Replacement of SWP and RH by LWP_p in the regression analysis, yielded R^2 = 0,39 and after addition of RH as an additional independent variable into the regression equation, 72% of the variation in LWP_{14} could be explained. The high similarity between the R^2 values obtained with either SWP and LWP_p together with RH in the regression equation was to be expected when the good correlation (R = 0,95) between SWP and LWP_p is considered.

The $\triangle$ Rs between T8 and T4 vines became statistically significant on 4/2/82

(Fig. 9c).   The low $\triangle$ Rs on the following measurement date, was possibly due to abnormal weather conditions on 16/2/82 (the RH was 55% at 14h00 on this date compared to the usual 30 - 40% during that time of day).

Although Rs correlated significantly with soil water status (SWC and SWP) and LWP both pre-dawn and at 14h00, these correlations were not very good. The variation in Rs was best explained by LWP_{14} $(R^2 = 0,44)$. However, combining other data sets obtained in the same vineyard with the present results revealed a much better relationship between Rs and LWP (Fig. 10).   This data suggest that the stomata remained open with increasing LWP until a threshold value of approximately -1600 kPa was reached.   Stomatal closure was rapid when this threshold LWP was exceeded.   This value is higher than the threshold value of -1300 kPa reported for both potted and field grown Shiraz (Kriedeman & Smart, 1971; Smart, 1974), or -1000 kPa found in a local study in a glasshouse (see previous chapters).   However, Liu et al. (1978) found stomatal closure of potted Concord at -1300 kPa, but in a Concord vineyard the stomata remained open at -1600 kPa.   This varia-tion among experimental results reconfirms the cautioning of Hsiao (1973) that plant adaptation to the environment could affect the water potential at which stress sets in.

The PA of T8 vines was already deleteriously affected by the soil water status on 28/1/82 as can be seen from the high PA difference ($\triangle$PA) (Fig. 9d).   Results of PA determinations on 20/1/82 were discarded due to instrument failure.   It was consequently impossible to determine whether photosynthesis was affected even earlier in the drying cycle.   Stomatal closure was clearly not the only factor responsible for the early decrease in photosynthetic activity since the Rs differential ($\triangle$Rs) was only 3,5 s cm^{-1} at that stage.   This finding supports the viewpoint that water stress not only causes stomatal closure and a consequent decline in CO_2 uptake, but that it can also inhibit CO_2 fixation through "injury to the

photosynthetic machinery" (Kramer, 1983). Probably due to a lack of suffi-
cient data, regression analysis failed to link PA to any of the measured pa-
rameters.

CONCLUSIONS

Plant parameters of water stress varied diurnally in dependence on environ-
mental factors such as relative humidity, wind, radiation and temperature.
Maximum Rs and Tl as well as minimum LWP values were generally found between
14h00 and 15h00, while Rs for stressed vines increased to high values during
this time of day.

Leaf exposure affected the measured plant parameters significantly. Leaf
water potential and Rs were respectively 20% and 53% higher on shaded leaves
compared to their fully sunlit counterparts. Water potential gradients
which theoretically can be the driving force for water movement also existed
between leaves and bunches. Although LWP_p in bunches were lower than in
leaves, the rate of change was more rapid in the latter organs and conse-
quently sunlit leaves displayed a lower water potential than bunches during
the middle part of the day. Bunches showed a delayed change in water poten-
tial and reached its minimum value later in the day than the leaves. Water
capacity differences between leaves and bunches offer one possible explana-
tion for the different response rates between the two organs. Should plant
resistances allow water movement from bunches to the leaves and subsequently
to the atmosphere under influence of a potential gradient, a delayed change
in bunch water potential would also result. The latter hypothesis of water
movement from bunches to leaves would also - at least partly - explain why
heavily cropped vines required more water than ones bearing less fruit as
was determined in the present study. However, the occurrence of such water
movement should be investigated further in order to determine its magnitude
and importance.

On the majority of measurement days the diurnal variation in LWP was best explained by Tl, although it (LWP) was also significantly correlated with RH, PAR and wind speed. The RH yielded the highest R^2 values during two days which were cooler and more humid than normal, while addition of Rs into the regression equation improved R^2 on two measurement days.

Linear regression analysis of plant and environmental variables during the period véraison to harvesting, showed that both SWP and LWP_p, with addition of RH gave a good explanation of the variation in LWP_{14} (R^2 = 0,70 and R^2 = 0,72 respectively). The relationship between LWP and Rs illustrated that the stomata remained open until a threshold LWP of approximately -1600 kPa was reached after which Rs values rose fairly rapidly. This threshold value of -1600 kPa was higher than the -1300 kPa reported by some researchers or the -1000 kPa found in local glasshouse studies, but should be accepted as a value, representative of Colombar under hot summer conditions.

Viewed over the duration of the ripening period, PA was poorly correlated with the other variables due to a large coefficient of variation (cv = 39%) in the PA data, but also due to a lack of data sets early in the drying cycle. There was, however, a tendency for PA to decrease at the same early date at which LWP_p indicated vine water stress. Stomatal resistance generally did not correlate well with the other variables except on two days when PAR and PAR + Tl explained 45% and 68% of the variation in Rs respectively.

Photosynthetic activity, determined by a portable field apparatus, correlated best with PAR, which could on average explain 43% of the variation in this parameter. At a stage when soil water had already been severely depleted, Rs made the largest contribution towards explaining variation in

photosynthesis (R^2 = 0,71).

Comparing vines subjected to an increasing soil water depletion, with a control, LWP_p proved to be a better indicator of vine water stress than LWP_{14} and Rs.   Pre-dawn LWP which was correlated significantly with both SWC (R = 0,89) and SWP (R = 0,95), fixed the development of vine water stress at a SWP of -64 kPa (average for the soil profile), which corresponded to a soil water regime between 25% and 50% for the soil of the experimental vineyard.   The LWP at 14h00 and Rs indicated a water stress situation only on the following measurement date.

LITERATURE CITED

AUSTIN, R.B. & LANGDON, P.C., 1967. A rapid method for the measurement of photosynthesis using $^{14}CO_2$. Ann. Bot. 31, 245-254.

BEGG, J.E. & TURNER, N.C., 1976. Crop water deficits. Adv. Agron. 28, 161217.

HILLEL, D., 1971. Soil and Water - Physical Principles and Processes. Academic Press, New York and London.

HOFäCKER, W., 1976. Untersuchungen über den Einfluss wechselnder Bodenwasserversorgung auf die Photosyntheseintensität und den Diffusionswiderstand bei Rebblättern. Vitis, 15, 171 - 182.

HOFäCKER, W., 1977. Untersuchungen zur Stoffproduktion der Rebe unter dem Einfluss wechselnder Bodenwasserversorgung. Vitis 16, 162.

HSIAO, T.C., 1973. Plant responses to water stress. Ann. Rev. Plant. Phys. 24, 519-570.

HSIAO, T.C., ACEVEDO, E., FERERES, E. & HENDERSON, D.W., 1976. Stress metabolism. Water stress, growth and osmotic adjustment. Phil. Trans. R. Soc. London. B. 273, 479-500.

KOZLOWSKI, T.T., 1972. Shrinking and swelling of plant tissues. In : T.T. Kozlowski (ed.) Water deficits and plant growth III. Academic Press New York, pp. 1-64.

KRAMER, P.J., 1983. Water relations of plants. Academic Press, New York.

KRIEDEMANN, P.E. & SMART, R.E., 1971. Effects of irradiance, temperature and leaf water potential on photosynthesis of vine leaves. Photosynthetica 5, 6-15.

LOVEYS, B.R. & KRIEDEMANN, P.E., 1974. Internal control of stomatal physiology and photosynthesis. I. Stomatal regulation and associated changes in endogenous levels of abscisic and phaseic acids. Aust. J.Plant Physiol. 1, 407 - 415.

LIU, W.T., POOL, R., WENKERT, W. & KRIEDEMANN, P.E., 1978. Changes in Photosynthesis, stomatal resistance and abscisic acid of Vitis labruscana through drought and irrigation cycles. Am. J. Enol. Vitic. 29, 239 - 246.

MONSELISE, S.P. & LENZ, F., 1980. Effects of fruit load on stomatal resistance, specific leaf weight, and water content of apple leaves. Gartenbauwissenschaft 38, 109 - 115.

OOSTERHUIS, D.M., 1982. Physiological and morphological indicators of crop water stress. Workshop on agronomic aspects of irrigation research, March 1-3, 1982. Co-ordinating Committee for Irrigation Research, Dept. of Agriculture, Pretoria.

PRATT, C., 1971. Reproductive anatomy in cultivated grapes - A review. Am. J. Enol. Vitic.

SCHOLANDER, P.F., HAMMEL, H.T., BRADSTREET, E.D. & HEMMINGSON, E.A., 1965. Sap pressure in vascular plants. Science 148, 339-346.

SHIMSHI, D., 1969. A rapid field method for measuring photosynthesis with labelled carbon dioxide. J. Exp. Bot. 20, 381 - 401.

SLATYER, R.O., 1967. Plant water relationships. Academic Press, New York.

SMART, R.E., 1974. Aspects of water relations of grapevine (Vitis vinifera). Am. J. Enol. Vitic. 25, 84 - 91.

SMART, R.E. & COOMBE, B.G., 1983. Water relations of grapevines. In : T.T. Kozlowski (ed.) Water deficits and plant growth VII, 137-196. Academic Press. New York.

VAN NORMAN, R.W. & BROWN, A.H., 1952. The relative rates of photosynthesis assimilation of isotopic forms of carbon dioxide. Am. J. Bot. 27, 691-709.

TABLE 1. Evapotranspiration of vines bearing different crop loads in the irrigation trial (10/12/81 - 6/1/82)

Crop Load (kg/vine)	Evapotranspiration (mm)
17,74	67,2
12,53	64,1
8,97	52,9
	LSD (P≤0,05) = 11,2

TABLE 2. Simple correlation coefficients between plant parameters and environmental factors on a typical day (4/2/82).

Independent Variables			Leaf Water Potential (LWP)		Photosynthetic Activity (PA)	
			r	F	r	F
X_1 =	RH	(%)	0,82	$26,35^{**}$	0,55	$5,78^{*}$
X_2 =	Wind	(km h^{-1})	−0,63	$8,36^{*}$	0,21	0,59
X_3 =	PAR	(μE $s^{-1}cm^{-2}$)	−0,85	$34,83^{**}$	0,74	$15,14^{**}$
X_4 =	T1	(°C)	−0,95	$131,70^{**}$	0,57	$6,12^{*}$
X_5 =	LWP	(kPa)	−	−	−0,53	$5,06^{*}$
X_6 =	Rs	(s cm^{-1})	−0,09	0,10	−0,62	$8,06^{*}$

* Significant ($P \leq 0,05$)

** Highly Significant ($P \leq 0,01$)

TABLE 3. Regression Analysis of relationships between variables during the diurnal variation in plant parameters and metereological factors

Date	Dependent Variable	Regression Equation	R	R^2
14/1/82	Leaf Water Potential	$Y = 2207,6547 - 113,8740\ X_4$	-0,97	0,93
	Stomatal Resistance	$Y = 11,9149 - 0,0075\ X_3$	0,78	0,57
	Photosynthetic Activity	$Y = 0,6946 + 0,0195\ X_3$	0,49	0,18
20/1/82	Leaf Water Potential	$Y = -1602,7693 + 13,6244\ X_1 - 28,3647\ X_6$	-0,84	0,67
	Stomatal Resistance	$Y = 10,3099 - 0,0042\ X_3$	0,70	0,45
28/1/82	Leaf Water Potential	$Y = 1240,8548 - 75,5202\ X_4$	-0,89	0,78
	Photosynthetic Activity	$Y = 0,1138 + 0,0556\ X_3$	0,67	0,40
	Stomatal Resistance	$-$	NS	NS
4/2/82	Leaf Water Potential	$Y = 1749,7982 - 95,1378\ X_4$	-0,95	0,90
	Stomatal Resistance	$-$	NS	NS
	Photosynthetic Activity	$Y = 21,5813 + 0,0139\ X_3 - 1,7482\ X_6$	0,83	0,64
16/2/82	Leaf Water Potential	$Y = -2128,8927 + 22,0780\ X_1$	0,52	0,22
	Stomatal Resistance	$Y = 49,1170 - 0,0155\ X_3 + 1,6442\ X_4$	0,85	0,69
	Photosynthetic Activity	$Y = 60,6912 - 0,9251\ X_1 + 0,0952\ X_3$	0,91	0,79

TABLE 3 (Continued)

Date	Dependent Variable	Regression Equation	R	R²
8/3/82	Leaf Water Potential	$Y = 1701,5541 - 94,6291\ X_4 - 13,8741\ X_6$	-0,87	0,71
	Stomatal Resistance	$Y = -9,5760 - 0,0174\ X_5$	-0,58	0,28
	Photosynthetic Activity	$Y = 27,7710 - 0,6722\ X_6$	-0,71	0,46
24/3/82	Leaf Water Potential	$Y = -1266,89 + 9,6189\ X_1 - 15,6084\ X_6$	-0,80	0,58
	Stomatal Resistance	$Y = 14,7196 - 0,0230\ X_5$	-0,67	0,41

Regression equations were obtained with stepwise regression analysis : Addition of more dependent variables in the equation gave no significant improvement of R^2.

X_1 = Relative Humidity = RH (%)
X_2 = Wind Speed = Wind (km h^{-1})
X_3 = Photosynthetic Active Radiation = PAR (μEm^{-2}s^{-1})
X_4 = Leaf Temperature = Tl (°C)
X_5 = Leaf Water Potential = LWP (kPa)
X_6 = Stomatal Resistance = Rs (scm^{-1})

TABLE 4. Regression analysis of the relationship between pre-dawn LWP (dependent variable) and various environmental factors and plant parameters determined at 14h00

Independent Variables			Mean	Standard Deviation	r	f	R	R^2	Regression Equation
X_1 =	SWC	(Mass %)	17,13	4,10	0,89	50,57[**]			
X_2 =	SWP	(kPa)	−34,2	44,7	0,95	120,83[**]	0,95	0,90	Y = −98,6541 + 3,3840 X_2
X_3 =	RH	(%)	35,9	10,7	0,25	0,89			
X_4 =	PAR	(μE s^{-1}m^{-2})	1153	485	−0,02	0,01			
X_5 =	Tl	(°C)	30,2	3,9	−0,09	0,10			
X_6 =	LWP$_{14}$	(kPa)	−1254	253	0,66	9,98[**]			
X_7 =	RS	(s cm^{-1})	43,29	32,2	−0,72	14,14[**]			

* Significant ($P \leqslant 0,05$)

** Highly significant ($P \leqslant 0,01$)

Regression equation was obtained with stepwise regression analysis : Addition of more independent variables in the equation gave no significant improvement of R^2.

TABLE 5. Regression analysis of the relationship between LWP at 14h00 (dependent variable) and various environmental factors and plant parameters determined at 14h00

Independent Variables	Mean	Standard Deviation	r	F	R	R^2	Regression Equations
X_1 = SWC (Mass %)	17,05	3,71	0,63	12,58[**]	0,78	0,56	$Y = -2447,2766 + 49,3475\ X_1 + 11,4182\ X_3$
X_2 = SWP (kPa)	-30,7	39,6	0,71	19,05[**]	0,84	0,70	$Y = -1463,6179 + 5,2820\ X_2 + 11,9882\ X_3$
X_3 = RH (%)	34,4	11,5	0,45	4,75[*]			
X_4 = PAR ($\mu E\ s^{-1}m^{-2}$)	1188	448	-0,31	2,00			
X_5 = Tl (°C)	30,6	3,7	-0,52	7,04[*]			
X_6 = Rs (s cm^{-1})	8,61	14,54	-0,68	16,41[**]	0,68	0,44	$Y = -1097,7863 - 13,4434\ X_6$
X_7 = LWP$_p$ (kPa)	-200	141	0,65	13,84[**]	0,85	0,72	$Y = -1408,0157 + 14,5918\ X_3 + 1,5339\ X_7$

[*]   Significant $(P \leqslant 0,05)$

[**] Highly Significant $(P \leqslant 0,01)$

Regression equations were obtained with stepwise regression analysis : Addition of more independent variables in the equation gave no significant improvement of R^2.

TABLE 6. Regression analysis of the relationship between stomatal resistance (dependent variable) and various environmental factors and plant parameters determined at 14h00

Independent Variables	Mean	Standard Deviation	r	F	R	R^2	Regression Equation
$1/X_1$ (X_1 = SWC in mass %)	0,0619	0,0162	0,58	9,79**			
X_2 = SWP (kPa)	−30,7	39,5	−0,65	8,27**			
X_3 = RH (%)	34,4	11,5	−0,30	1,84			
X_4 = PAR ($\mu Es^{-1}m^{-2}$)	1189	448	0,18	0,60			
X_5 = T1 (°C)	30,6	3,7	0,38	3,20			
X_6 = LWP_{14} (kPa)	−1213	287	−0,68	16,41**	0,68	0,44	$Y = -33,2289 - 0,03447\ X_6$
X_7 = LWP_p (kPa)	− 200	141	−0,62	12,07**			

* Statistically significant (P ≤ 0,05)

** Statistically highly significant (P ≤ 0,01)

Regression equations were obtained with stepwise regression analysis : Addition of more independent variables in the equation gave no significant improvement of R^2.
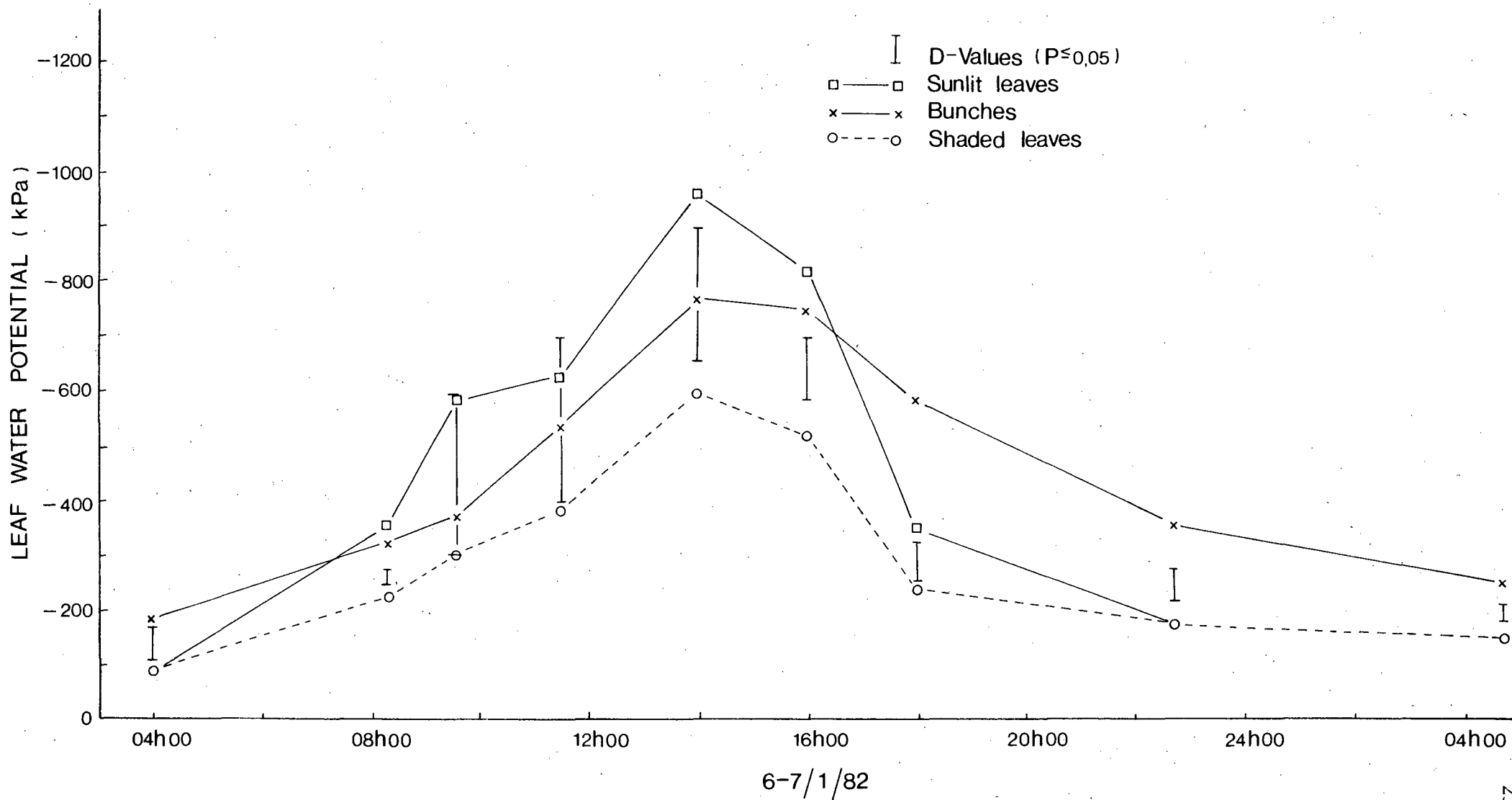
Fig. 1: Diurnal variation in the water potential of leaves and bunches of vines at a 90 % soil water regime (T4).
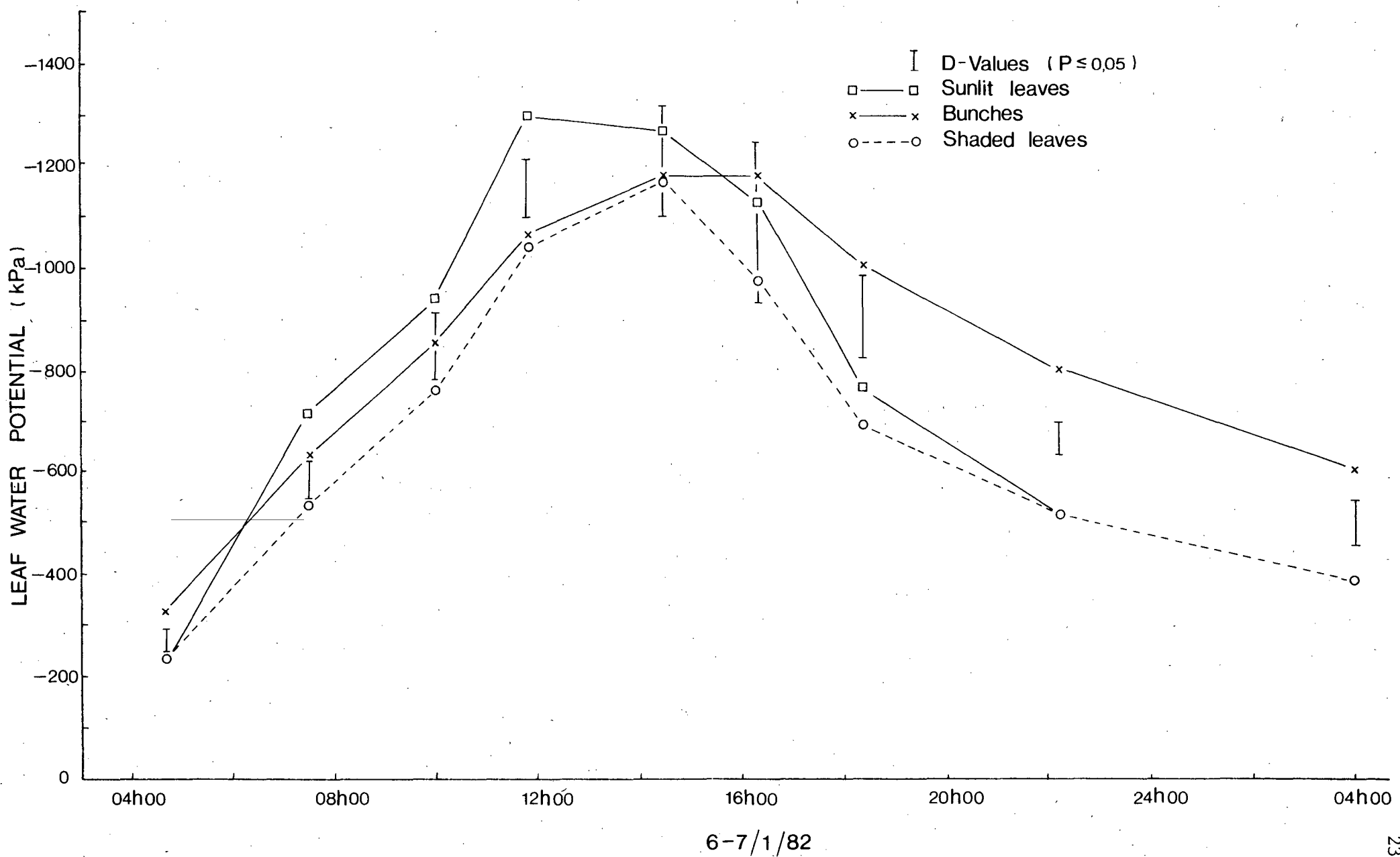
Fig. 2: Diurnal variation in the water potential of leaves and bunches of vines at a 25 % soil water regime (T1).
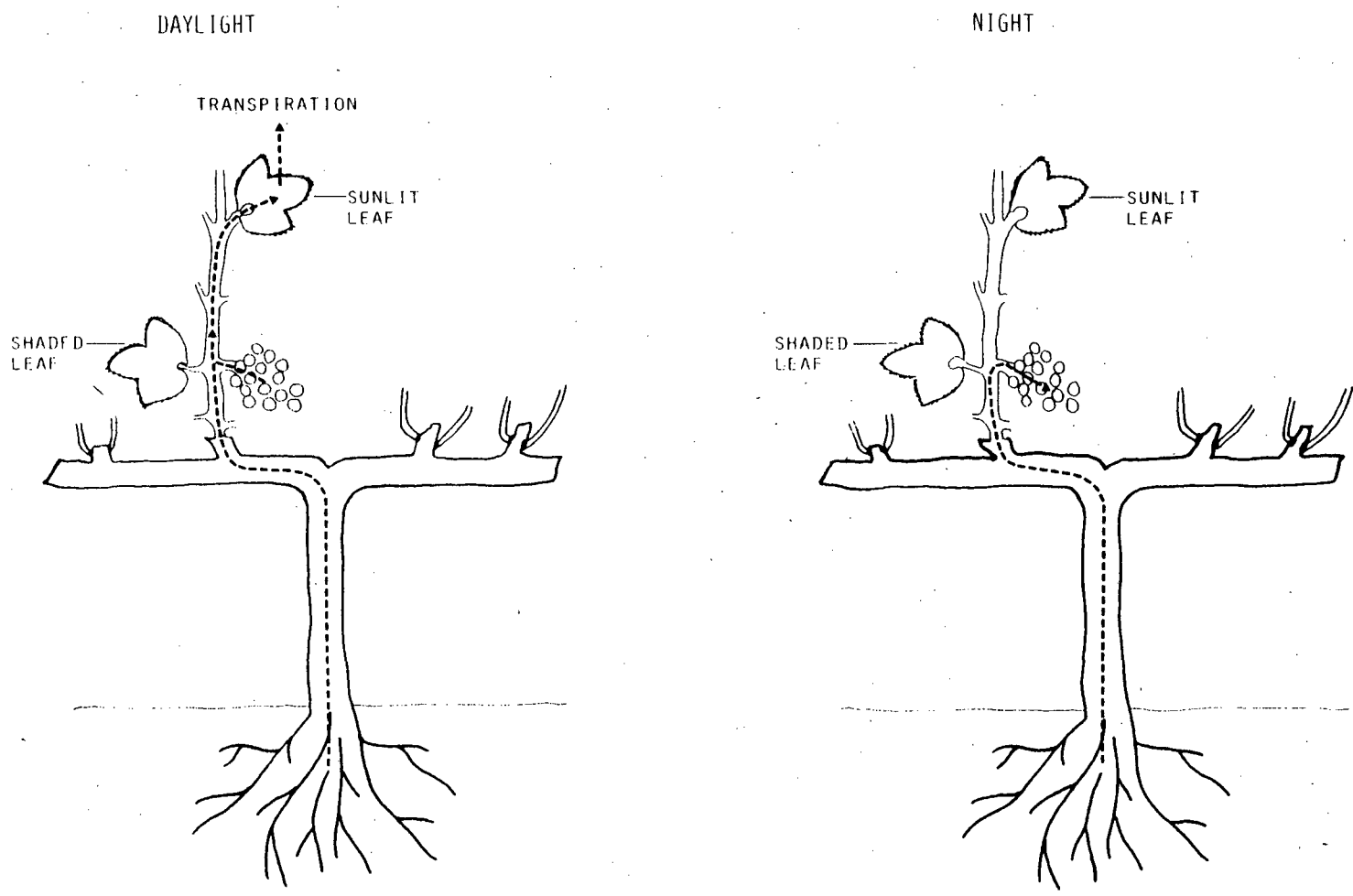
Fig. 3: Schematic presentation of hypothetical water flow in a grapevine during the day and at night.
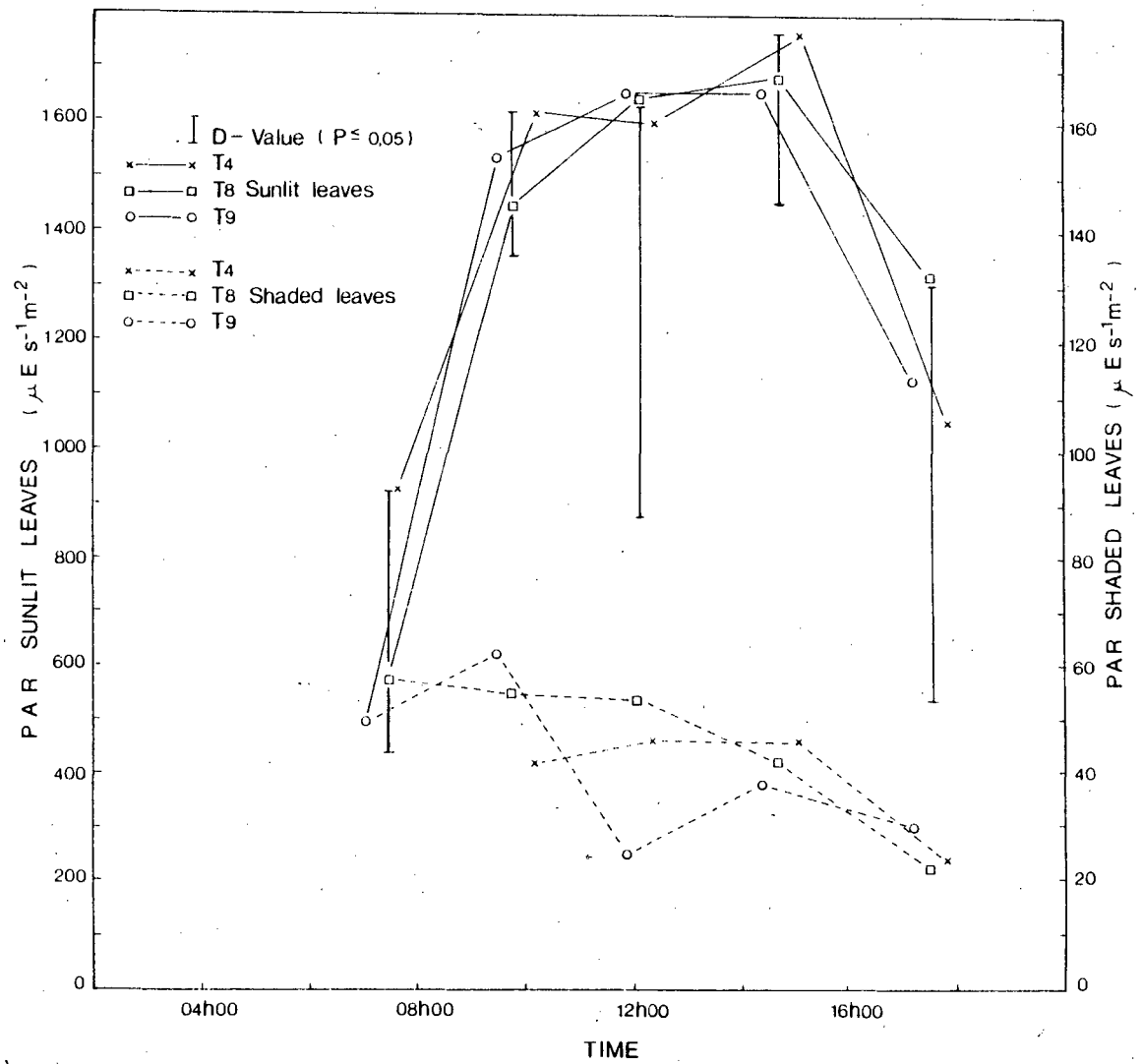
Fig. 4: Photosynthetic active radiation (PAR) above leaves used
for the determination of vine water stress. (4/2/82)
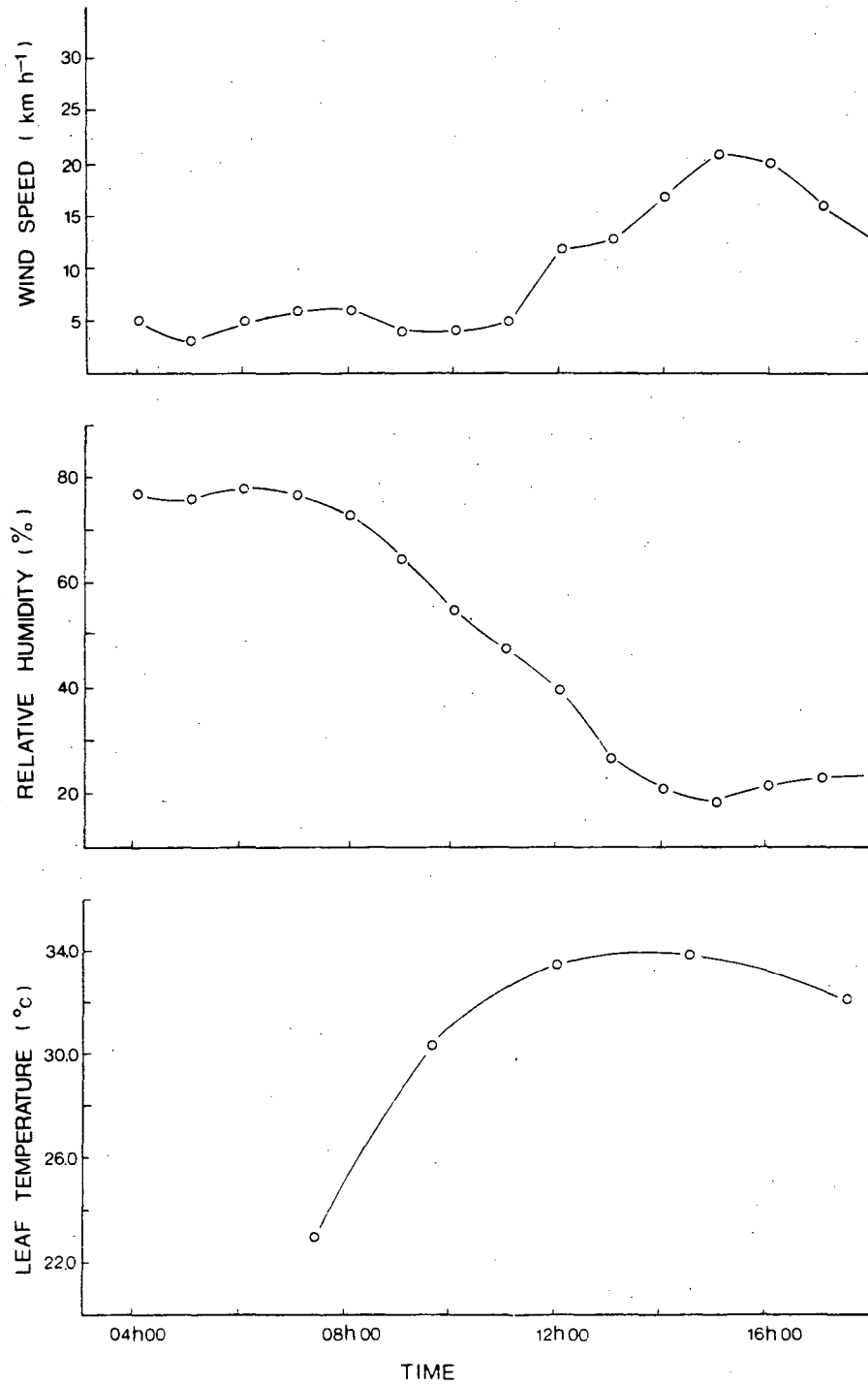
Fig. 5: Variation in climatic factors and leaf temperature in the experimental vineyard on a typical measurement day (4/2/82).
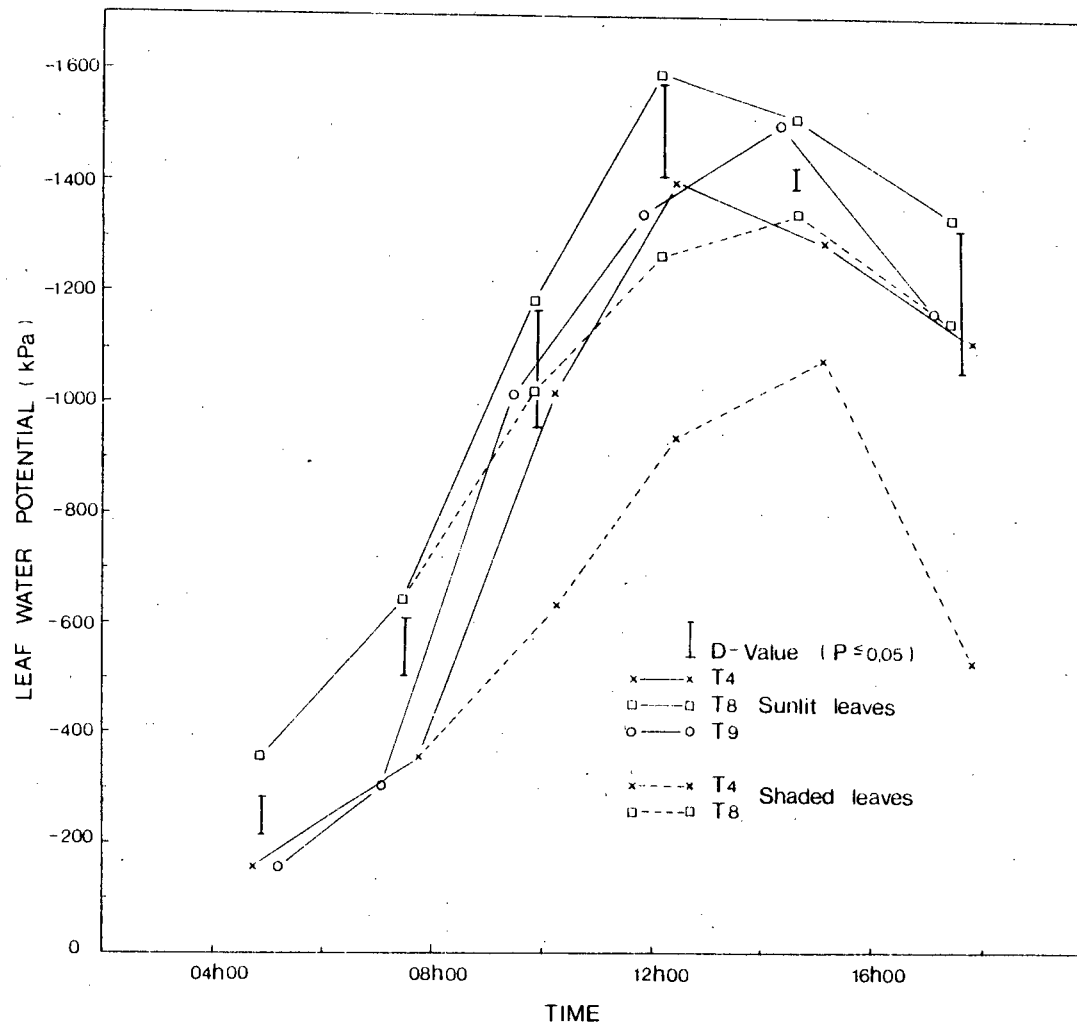
Fig. 6:   Diurnal variation of leaf water potential in the experimental
vineyard on a typical measurement day (4/2/82).
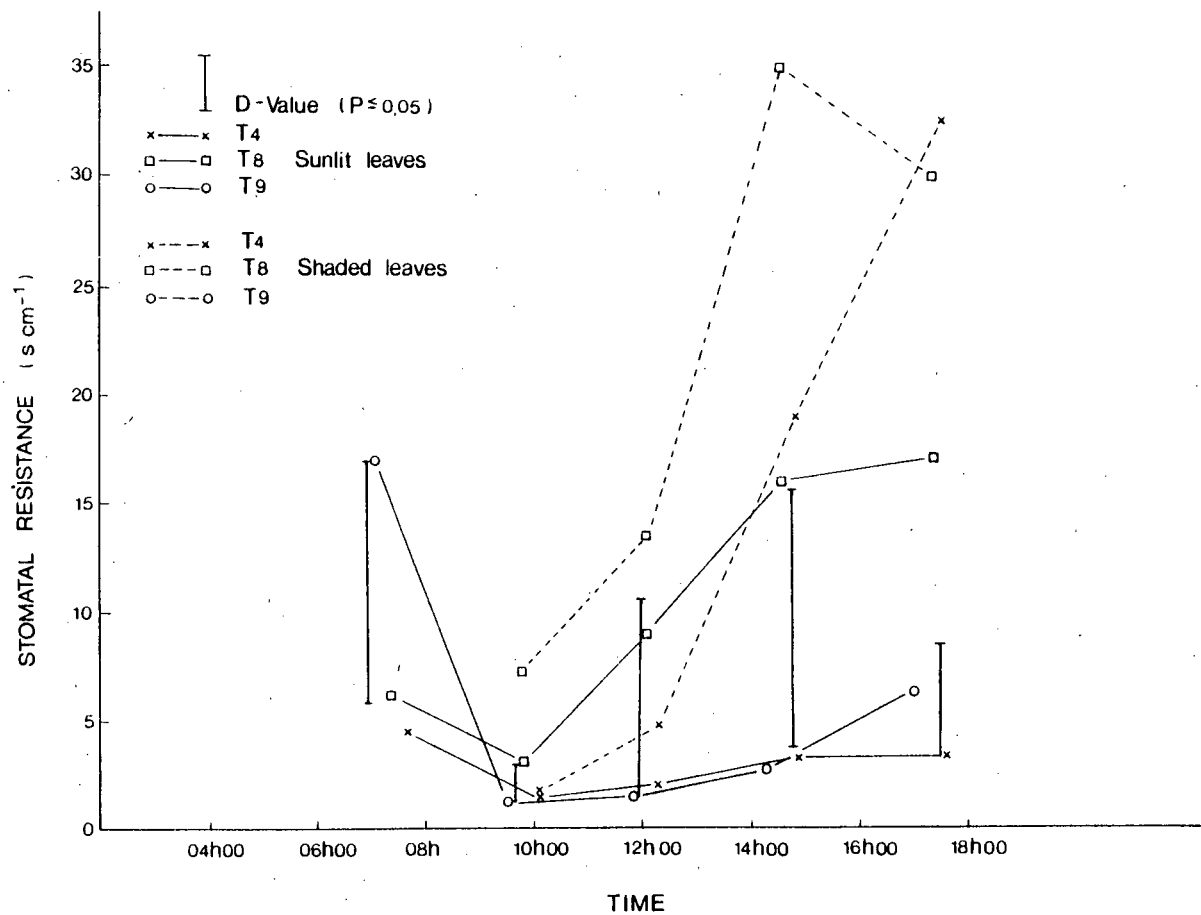
Fig. 7: Diurnal variation of stomatal resistance in the experimental
vineyard on a typical measurement day (4/2/82).
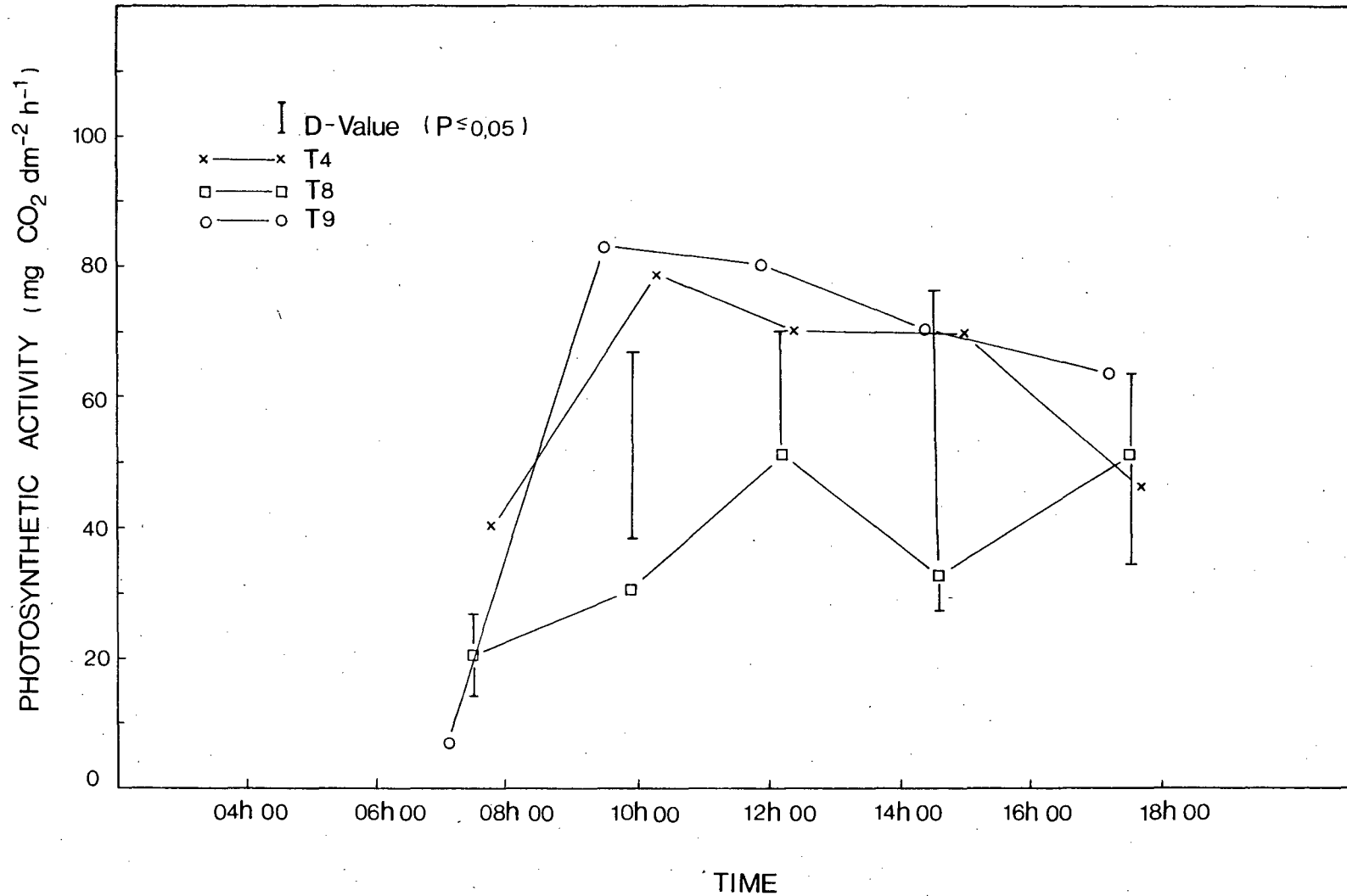
Fig. 8: Diurnal variation of photosynthetic activity in the experimental vineyard on a typical
measurement day (4/2/82).
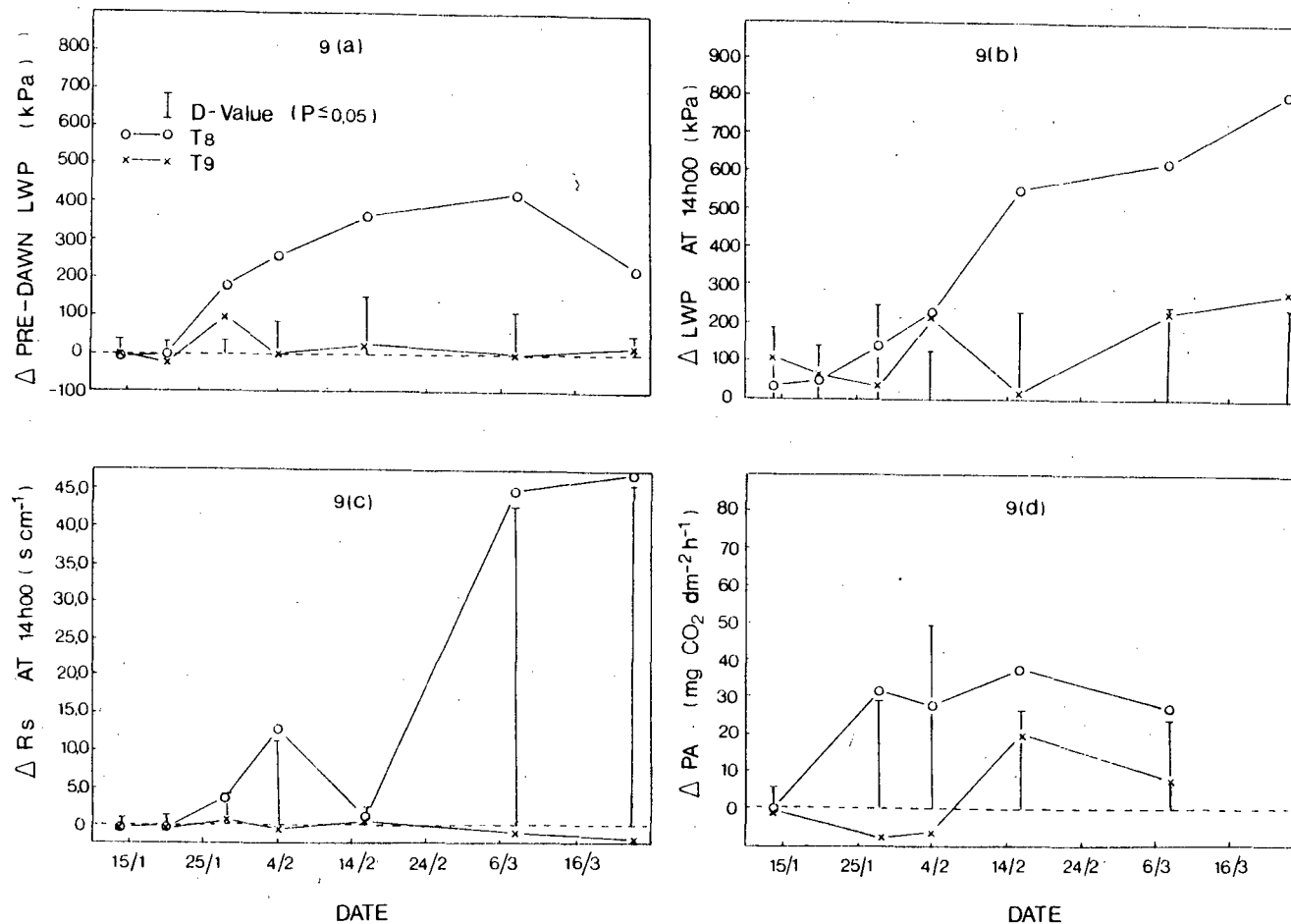
Fig. 9: Plant parameter differentials (Δ) of two irrigation treatments compared
to a well-watered control (T4) during the ripening stage of the
experimental vineyard.
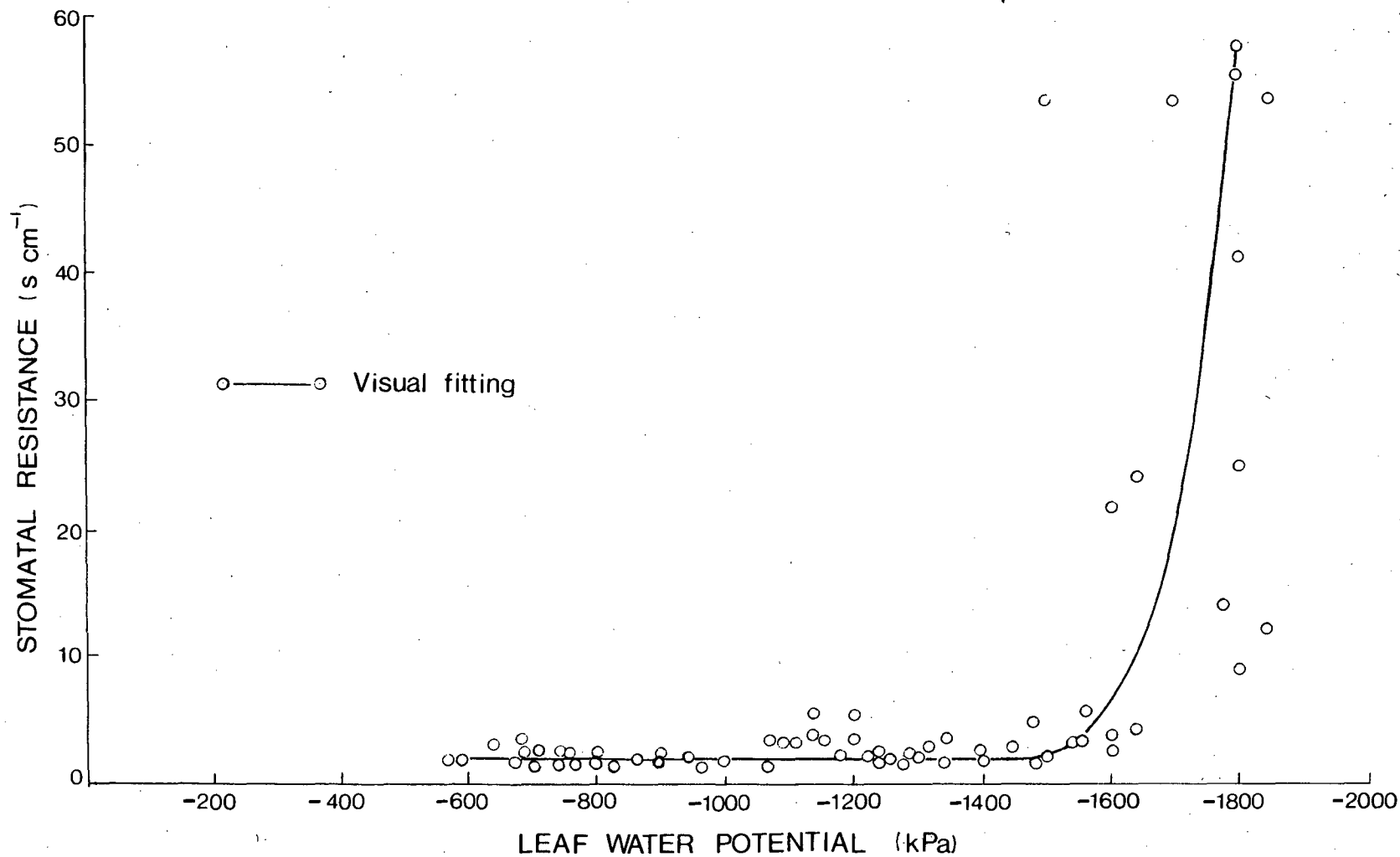
Fig. 10:   Visual fitting to indicate the relationship between leaf water potential and stomatal resistance of sunlit leaves in the irrigation trial at Robertson

CHAPTER 7

CANOPY TEMPERATURE AS A MOISTURE STRESS INDICATOR IN VINES

INTRODUCTION

A reliable and easily obtainable measure of plant moisture stress is the best approach for efficient irrigation scheduling in any crop. Instruments currently in use are almost exclusively based on the measurement of soil moisture such as tensiometers, or computations of meteorological data, both methods giving only an indirect indication of the probable plant moisture stress.

When a plant lacks water its stomata close, principally due to a lack of turgidity in the guard cells. Dissipation of energy by transpiration is thereby reduced, causing leaf temperature to rise. It should, therefore, be feasible to use leaf temperature as an indicator of water stress. The early problems associated with the measurement of this variable, when primarily contact sensors such as thermocouples were used, were outlined by Fuchs & Tanner (1966) who pointed out that one of the most serious problems was the difficulty of adequate sampling when canopies were to be studied. Many of these difficulties have been overcome with the development of remote sensing of surface temperatures through thermal radiation measurements, utilising the direct relationship between the surface temperature of an object and the electromagnetic radiation emitted from it. The introduction of the infrared thermometer has, to date, indicated remote sensing to be a promising approach to the monitoring of moisture stress in a crop and ultimately as a guide for irrigation scheduling (Ehrler, 1973; Sandhu & Horton, 1978; Idso, Jackson & Reginato, 1977; Gardner, 1979; Jung & Scott, 1980; Jackson, Idso, Reginato & Pinter, 1981; Mottram, de Jager & Duckworth,

1984; Berliner, Oosterhuis & Green, 1984).

Its advantages include its ability to give rapid and accurate surface tempe-
rature measurements without the problems of equilibration time and possible
temperature change because of measurements, associated with contact sensors
(Berliner, Oosterhuis & Green, 1984). It incorporates an emissivity adjust-
ment control which allows inbuilt correction to be made for the fact that
all objects emit less infra-red radiation than would a theoretically perfect
radiator, (a black body) at the same temperature.

Several indices for the prediction of crop water status from measurements of
canopy temperature have been proposed. Jackson, et al (1981) developed a
crop water stress index using canopy to air temperature differences and
their dependence on atmospheric vapour pressure deficit. This approach has
the disadvantage that the values can be affected by changing atmospheric
conditions, notably net radiation and wind speed. Nevertheless, it was
found by Mottram, de Jager & Duckworth (1984) to be a successful and prac-
tical stress index for maize under South African conditions.

An alternative approach was developed by Fuchs & Tanner (1966) who compared
the measured canopy temperature to that of a reference, non-stressed plot.
In this way the interference of confounding factors, such as changing atmos-
pheric conditions, could be avoided and the differences in canopy tempera-
ture between plots could be related to the differences in leaf water poten-
tial (LWP) and stomatal resistance (Rs). The reference plot approach was
used in wheat by Berliner, Oosterhuis & Green (1984) who found this method
most promising despite the practical problems imposed by the upkeep of a
well-watered plot. The scatter of observations was comparable to that ob-
tained when more complex approaches involving additional routine measure-
ments were used.

The object of this study was to evaluate the use of the infra-red thermo-meter in vineyards by investigating the relationship between vine tempera-ture, soil moisture conditions and some plant physiological parameters relating to moisture stress.

<div align="center">MATERIALS AND METHODS</div>

Experimental Plots

The investigation was carried out in a fully bearing, trellised, Colombar vineyard, which itself comprises a long-term irrigation trial at Robertson (see Chapter 4 for details of experimental layout and treatments). Conse-quently much data relating vine performance to various moisture regimes were readily available. Initially two plots were selected to represent the two extremes of water availability. Within each plot, which comprised a test row between two buffer rows, five standard vines were selected, on which measurements would be made throughout the season. The test plot (T1) was irrigated at bud burst and then again six weeks later, immediately prior to the commencement of the investigation. Having been watered (by microjets) to field capacity to the full rooting depth, the soil was allowed to dry out for the following four weeks, during which time, at approximately weekly intervals, the various plant and soil parameters described below, were measured. Concurrent measurements were made on a control plot (T4) irriga-ted sufficiently throughout the investigation period in order to maintain a 90% soil moisture regime.

After completion of the first series of measurements the test plot (T1) was irrigated again at véraison and, in a second phase of the investigation, allowed to dry out for a seven week period. This second drying cycle was followed by two irrigations of 50mm each on 12/3/83 and 23/3/83, respective-

ly. The latter two weeks were included in the experiment in order to deter-
mine the effect of plant recovery from water stress on the parameters of
plant water status. Measurements were continued throughout these cycles un-
til harvesting.

In order to affect a more rapid dessication of the soil, a trickle irrigated
plot (T10) was added during the second phase of the investigation. This
plot was divided into a control (trickle irrigation continued) and a test
area (all irrigation stopped by blocking the tricklers). It was assumed, as
the area of soil wetted by trickle irrigation is restricted to that around
the immediate area of the roots, that once the tricklers were blocked, the
time before appreciable moisture stress was experienced by the vines would
be less than for the micro-jet irrigated plot used initially. As with plots
T1 and T4, five representative vines were selected from both the test row
and the control row. After five weeks, which coincided to a week before
harvest, the test row was again irrigated. A further set of measurements
was collected the day before harvesting.

Measurements of Soil Moisture Status

Tensiometers were installed at the four depths viz., 0,20m, 0,40m, 0,60m and
0,80m, at equivalent distances from each of the five vines in the initial
test plot (T1). The soil water potential was determined on the control plot
(T4) by only one set of four tensiometers at the same depths as in T1. In
the trickler plot, (T10), four tensiometers were installed at the equivalent
depths next to one of the five vines from each of the test and the control
rows. Readings were, with some exceptions, taken daily at 08h00 until the
measuring range of the tensiometers was exceeded.

Access tubes for the neutron moisture probe were installed at a distance of
approximately 0,35m from each of the five vines (to correspond with a ten-
siometer position) in the two test plots (T1 and T10). Readings were taken

from the same four depths viz., 0,20m, 0,40m, 0,60m and 0,80m on days when the plant parameters were being measured.

Gravimetric soil water determinations were also carried out on "measurement days" for each vine in the two test plots and usually for at least two vines in the control plots, at the same four depths.

Measurement of Plant Water Status

It was decided to have three measurement periods per day, in addition to the pre-dawn determination of leaf water potential, viz., 10h00, 12h00 and 14h00, the latter representing the hottest (most stressed) part of the day. These times were subsequently reduced to only include the pre-dawn and the 14h00 readings.

Leaf water potentials were measured as described previously (Chapter 6). The leaves for the pre-dawn readings were covered with a plastic bag and aluminium foil the previous night in order to allow them to achieve maximum turgidity. One recently-matured, sunlit leaf per vine (five per plot) was used, the same leaf having previously been used for the measurement of Rs with an automatic diffusion porometer.

Vine temperature was determined with a Telatemp Model AG-42 infra-red thermometer, initially incorporating a sunlit leaf, a shaded leaf and the leaf canopy, and then latterly, just the canopy. Details of the operation of the infra-red thermometer are given in a separate section below.

During the initial phase of the investigation an estimation of the difference in berry growth rate between the test plot (T1) and the control plot (T4) was made. The fresh masses of thirty-two berries per vine, randomly selected

from marked bunches, were recorded on measurement days throughout December and growth curves constructed.

Analyses of variance were conducted on plant parameter data in order to establish significant differences among treatments. In addition, linear regression analyses were done on the data with the aim of quantifying relationships between canopy temperature and the other plant physiological parameters.

Use of the Infrared Thermometer

The Telatemp AG-42 infra-red thermometer, with a temperature range of -30°C to +100°C and an accuracy of $\pm0,5$°C has a viewing angle of 4°, which results in a target diameter to distance ratio of 1 : 20. This means that at a distance of 20 m, the thermometer measures the temperature of a 1m diameter spot, perpendicular to the line of sight of the instrument. If used at an acute angle of incidence, the shape of the spot on the target surface becomes elliptical instead of round. Calibration of this thermometer over a water bath yielded a maximum deviation of only 0,2°C from the water bath temperature at 25°C.

By means of a termocouple situated at the front of the instrument, it can also measure the difference in temperature between the target surface and the prevailing ambient temperature. Throughout the early stages of the investigation it was found that the air temperature measured with an accurate mercury thermometer and that from the infrared thermometer differed, an experience also encountered by other workers (Mottram, De Jager & Duckworth, 1984). This was thought to be due to heat being conducted from the thermometer's external casing towards the air temperature sensor.

Infra-red thermometers must make provision for the fact that most surfaces are not perfect radiators, and that an emissivity factor must be incorporated

into the measurements. Throughout the course of this investigation an emissivity of 0,97 was assumed for the plant surface, on the basis of findings by Fuchs & Tanner (1966).

To measure the temperature of a sunlit or shaded leaf, the infrared thermo meter was held perpendicular to, and about 0,20m away from the leaf surface. This resulted in a target spot of 10mm diameter. Three or more readings were taken per leaf. In addition, canopy temperature (CT) per vine was determined, initially by holding the instrument at a distance of 2 m and later by clamping it to a stand.

The canopy readings were all taken with the sun behind the operator, care being taken to eliminate any sky or soil from the field of view (which markedly affects the temperature read-out), and to avoid as far as possible the inclusion of any berries in the field of view as they were usually found to be at a different temperature than the leaf canopy.

RESULTS AND DISCUSSION

Temperature measurements carried out in the vineyard for six days at 12h00 and 14h00 showed that sunlit leaves were significantly warmer than either shaded leaves or the canopy with no significant difference between the latter two positions. Mean temperatures and their standard deviation were as follows:

Sunlit leaves	=	33,02°C $\pm$ 1,90
Canopy	=	30,85°C $\pm$ 1,09
Shaded leaves	=	30,19°C $\pm$ 0,93

The relatively low temperature of the canopy resulted from the configuration

of the trellising system which caused the infra-red thermometer to "see" a great deal of shade when the canopy was viewed from the sides. Measurements of canopy temperature from overhead would have yielded values closer to that of sunlit leaves, as was confirmed during a few tests.

A further difference among temperatures measured at the three positions on the vines, was the higher standard devaition found in the case of sunlit leaves. Apparently the orientation of the leaf blade relative to the sun is the cause for the increased temperature variation among leaves. Measurements made on individual leaves were eventually discarded in favour of canopy measurements since the latter is more representive of the vine as a whole. In addition, with regard to the future use of the infra-red thermometer as an aid to irrigation scheduling, a canopy measurement would be more practical.

Measurements taken at 14h00 on T1 and T4 plots during the different drying cycles are presented in Fig. 1, pre-dawn values of leaf water potential (LWP_p) in Fig. 2 and data for trickler plots in Fig. 3. These absolute values of the plant parameters of water stress, especially temperature, varied greatly throughout the investigational period depending on the prevalent atmospheric conditions. Consequently elimination of the atmospheric effect on plant parameters of water stress was attempted by calculating differentials through subtraction of test plot values from control plot values.

Experiment 1 (1/12/82 - 29/12/82)

The difference in SWC ($\triangle$SWC) between T1 and T4 (Fig. 4a) increased during the course of the experiment although the two plots were equally wet at the commencement of the drying cycle (Fig. 4a). Both LWP_p differentials

($\triangle LWP_p$) (Fig. 4b) as well as CT differentials ($\triangle CT$) (Fig. 4c) corre-lated significantly with $\triangle SWC$ ($r = 0,85$ and $r = 0,98$ respectively). Soil water content differentials could in fact explain 97% of the variation in $\triangle CT$ (Table 1). In contrast, $\triangle LWP$ at 14h00 ($\triangle LWP_{14}$) (Fig. 4b) follo-wed a course which reflects neither the high soil water content on T1 plots at the beginning of the drying cycle nor the very dry conditions at the con-clusion of this experiment. Similarly, Rs differentials ($\triangle Rs$) (Fig. 4d) did not correlate significantly with the other measured parameters, due to the unexpected low value on 29/12 at a stage when all the other parameters indicated water stress conditions.

The onset of plant water stress was best indicated by CT (Fig. 4c). Canopy temperature differentials became significantly positive (1,3°C) for the first time on 17/12 and increased to a maximum of 1,7°C on 29/12. The pre-dawn values of $\triangle LWP$ only became significant on 29/12 for the first time, but Rs also significantly indicated stress on 17/12. Any doubt as to the onset of water stress in the grapevines was eliminated by the berry growth curves of the test (T1) and control (T4) plots (Fig. 5). Although the berry fresh mass of T4 was higher than that of T1 at the beginning of the experi-ment, the berry mass differentials remained constant until 13/12, indicating that the mass of berries from both control and test plots increased at the same rates. From then onwards i.e. on 17/12 and 29/12 the berry growth rate of T4 berries were much higher than that of T1 berries due to water stress in the latter vines.

Acceptance of 17/12/82 as the first date on which water stress was measured, coincided with a $\triangle SWC$ of 4,89% which in turn corresponded to a 36% soil water regime.

Experiment 2 (19/1 - 28/3)

The course of the second drying cycle, which occurred during the ripening stage of the grapes, followed by soil water replenishment during the three weeks before harvesting, is clearly illustrated by $\triangle$ SWC (Fig. 6a). The plant parameters of water stress responded well to the changing soil water status. Pre-dawn values of $\triangle$ LWP (Fig. 6b) followed the variation in soil water status the closest (r = 0,82). Although $\triangle$ LWP$_{14}$ were not significantly correlated with $\triangle$ SWC, they clearly showed increasing vine water stress due to soil water depletion as well as the expected decrease caused by soil water replenishment. During the drying cycle T1 vines reached a minimum LWP of -2000 kPa on a very hot day (11/3/83) at a stage when the soil was very dry (Fig. 1).

Canopy temperature differentials, similar to Experiment 1, correlated significantly (r = 0,65) with $\triangle$ SWC (Table 1). Although $\triangle$ CT on 28/1 was unexpectedly large (statistically not significant) it should be discarded in determining the onset of water stress, in the light of values obtained on the following two measurement dates (Fig. 6c). The temperature difference between test and control plots reached a maximum of 3,2°C on 11/3/83. This parameter was also significantly correlated with $\triangle$ Rs (r = 0,83) (Table 2).

Values of all plant parameters dropped considerably after the first irrigation (50mm) on 12/3, but the T1 vines remained stressed in comparison with the T4 control. A second irrigation on 22/3 was adequate to restore the LWP and Rs of the stressed vines to the same levels found in the unstressed control vines. Values of $\triangle$ CT were the exception in this case; it remained at 1,1°C above the zero line (Fig. 6).

Onset of water stress was indicated by both canopy temperature and stomatal resistance to have occurred on 23/2/83 at a stage when $\triangle$ SWC was 5,14% corresponding to a soil moisture regime of 33%. However, plant water stress

had already been indicated by significant values of $\triangle$LWP at 14h00 on 16/2 (Fig. 6b) and on 2/2 by pre-dawn $\triangle$LWP. Since some uncertainty exists regarding the effect of 25mm of rain which fell during the day and night before the measurement day on 2/2, the 16th February should be considered as the first date on which plant water stress was detected. The onset of water stress at the latter date indicated a soil water regime of 46,3% which is considerably higher than that indicated by CT.

Experiment 3 (Tricklers)

Data on soil water status and the plant parameters measured at 14h00 are presented in Fig. 3. At the start of this phase of the investigation, the soil water content of the test plots was already approaching PWP. This large difference in soil water content between control and test plots was maintained throughout and was only eliminated by an irrigation on 23/2/83 (Fig. 7a). All plant parameters indicated significant differences in vine water stress between test and control plots at 14h00. Relieving of stress by water application was also reflected in the plant parameter differentials. The last set of measurements (28/3) was the only data set which showed no significant differences between test and control plots (Fig. 7).

During this phase of the investigation, CT varied between 36,7°C and 20,6°C. Despite this wide range, $\triangle$CT were significant both at high and low absolute values, thus emphasizing the applicability of this parameter as an indicator of vine water stress. Due to the lack of a sufficient number of data points, the regression coefficient (r = 0,73) between $\triangle$CT and $\triangle$SWC was not significant (Table 1).

Compiled Data

A statistical analysis of all data collected in the three experiments included in the investigation on the infra-red thermometer, yielded a more reliable picture of how CT was related to the other parameters of water stress. Compilation of all data gave a regression coefficient of 0,73 between △SWC and △CT (Table 1). The SWC differential could explain 53% of the variation in △CT. This linear relationship is illustrated graphically in Fig. 8.

Despite non-significant regression coefficients between △CT and △Rs in Experiments 1 and 3, a significant correlation coefficient (r = 0,63) was obtained when the relevant data for all three experiments were analysed together (Table 2, Fig. 9). However, △RS could still explain only 39% of the variation in △CT.

Differentials of CT and LWP were generally poorly correlated but when absolute values of both parameters were compared, significant regression coefficients were obtained (Table 3). This relationship was linear with r = -0,68 for all data. Explanation of only 47% of the variation in CT by LWP once again stresses the interwoven relationships between the many soil, plant and atmospheric factors which contribute to plant water stress in the field.

CONCLUSION

The infra-red thermometer proved itself to be reliable, easy to operate and an accurate instrument for the measurement of plant temperature. Canopy temperature measured with the infra-red thermometer was utilised successfully to indicate water stress in grapevines. This was possible by comparing a well irrigated control plot to one subjected to a continuously increasing water stress during a drying cycle. This approach was aimed at eliminating

the overriding effect of climatic factors and isolating the effect of plant water stress on CT. The maximum ΔCT obtained between stressed and control plots were 3,2°C. Despite the small differences in CT, the high accuracy of the infra-red thermometer and the low standard deviation of only 0,71°C (coëfficient of variance = 2,4%) over the temperature range 30-40°C made the detection of temperature increases due to water stress possible and practical.

The onset of water stress, taken to be the statistically significant difference between the control and stressed plots, was indicated simultaneously by CT and Rs. In one of the two experiments LWP_p indicated the onset of water stress in the grapevine at an earlier stage than canopy temperature.

Canopy temperature differentials were significantly, positively and linearly correlated with both ΔSWC and ΔRs. Considerable variation in the data sets caused both parameters to explain a relatively small percentage of the variation in ΔCT.

A critical ΔCT at which grapevines should be irrigated in order to prevent crop losses can provisionally be given. From the relationship between ΔCT and ΔSWC, it can be calculated that a 50% soil water regime, generally being used by farmers, corresponds to ΔCT = 1,16°C. Acceptance of a critical range of soil water regimes between 30% and 50% as is being suggested from this investigation, a ΔCT range of 1,62 - 1,16°C is indicated. The possibility of applying CT as an indicator of plant water stress to irrigation scheduling to maintain the soil water regime close to FC seems small. The critical values of ΔCT proposed above, should be tested and refined further before it can be applied in practice.

The approach adopted in this experiment required the maintenance of a well

watered control plot. This may seem cumbersome, but according to Berliner, Oosterhuis & Green (1984) this disadvantage is overridden by the benefits of standard atmospheric conditions and the fact that no additional metereological measurements required by other approaches, are necessary. Nevertheless, the method which is based upon canopy/air temperature differences (Aston & Van Bavel, 1972) and developed into defining a crop water stress index to account for the vapour pressure deficit should also be investigated with regard to grapevines.

LITERATURE CITED

ASTON, A.R. & VAN BAVEL, C.H.M., 1972. Soil surface water depletion and leaf temperature. Agron. J. 64, 368-373.

BERLINER, P., OOSTERHUIS, D.M. & GREEN, G.C., 1984. Evaluation of the infrared thermometer as a crop stress indicator. Agric. Forest. Meteor. 31, 219-230.

EHRLER, W.L., 1973. Cotton leaf temperatures as related to soil water depletion and metereological factors. Agron. J. 65, 404-409.

FUCHS, M. & TANNER, C.B., 1966. Infrared thermometry of vegetation. Agron. J. 58, 597-601.

GARDNER, B.R., 1979. Plant and canopy temperatures in corn as influenced by differential moisture stress. M.Sc. Thesis, Dept. of Agric. Eng., Univ. of Nebraska.

IDSO, S.B., JACKSON, R.D. & REGINATO, R.J., 1977. Remote-sensing of crop yields. Science 196, 19-25.

JACKSON, R.D., IDSO, S.B., REGINATO, R.J. & PINTER, P.J., 1981. Canopy temperature as a crop water stress indicator. Water Resources Res. 17, 1133-1138.

JUNG, P.K. & SCOTT, H.D., 1980. Leaf water potential, stomatal resistance and temperature relations in field-grown soybeans. Agron. J. 72, 986-990.

MOTTRAM, R., DE JAGER, J.M. & DUCKWORTH, J.R., 1984. Evaluation of a water stress index for maize using an infrared thermometer. S. Afr. J. Plant and Soil. 1 (4), in press.

SANDHU, B.S. & HORTON, M.L., 1978. Temperature response of oats to water stress in the field. Agric. Metereol. 19, 329-336.

TABLE 1.   Relationship between differentials of canopy temperature (ΔCT) at 14h00 and soil water content (ΔSWC)

		Experiment 1 Dec. 1982	Experiment 2 Jan. 1983	Experiment 3 Tricklers	All Data
Regression Coefficient	(r)	0,98**	0,62*	0,73	0,73**
Coefficient of Determination	(R^2)	0,97	0,39	0,53	0,53
Mean & Standard Δ SWC	(x)	3,66 ± 2,11	4,77 ± 2,37	6,21 ± 3,70	4,78 ± 2,61
Deviation Δ CT	(y)	0,24 ± 1,44	1,31 ± 1,24	1,77 ± 1,08	1,13 ± 1,32

SWC   =   Soil Water Content   (%)

CT   =   Canopy Temperature   (°C)

*   =   Significant   (P $\leq$ 0,05)

**   =   Highly Significant   (P $\leq$ 0,01)

NS   =   Not Significant

TABLE 2. Relationship between differentials of canopy temperature ($\triangle$CT) and stomatal resistance ($\triangle$RS) at 14h00

	Experiment 1 Dec. 1982	Experiment 2 Jan. 1983	Experiment 3 Tricklers	All Data
Regression Coefficient (r)	0,50 NS	0,83[**]	0,16 NS	0,63[**]
Coefficient of Determination (R^2)	0,25	0,69	0,02	0,39
Mean & Standard Deviation $\triangle$RS (x)	0,24 ± 0,52	1,22 ± 1,27	2,42 ± 2,06	0,97 ± 1,19
$\triangle$CT (y)	0,24 ± 1,44	1,45 ± 1,22	1,77 ± 1,08	1,13 ± 1,36

RS   = Stomatal Resistance (s cm^{-1})

CT   = Canopy Temperature (°C)

*   = Significant   (P $\leqslant$ 0,05)

**   = Highly Significant (P $\leqslant$ 0,01)

NS   = Not Significant

TABLE 3. Relationship between canopy temperature (CT) and leaf water potential (LWP) determined at 14h00

	Experiment 1 Dec. 1983	Experiment 2 Jan. 1983	Experiment 3 Tricklers	All Data
Regression Coefficient (r)	−0,56 NS	−0,64**	−0,81**	−0,68**
Coefficient of Determination (R^2)	0,32	0,41	0,65	0,47
Mean & Standard Deviation ⎤ LWP (x)	−1408 ± 213	−1467 ± 246	−1488 ± 227	−1474 ± 237
⎦ CT (y)	28,82 ± 4,33	30,56 ± 3,79	31,63 ± 3,38	30,9 ± 3,66

LWP = Leaf Water Potential (kPa)

CT = Canopy Temperature (°C)

* = Significant (P ≤ 0,05)

** = Highly Significant (P ≤ 0,01)

NS = Not Significant
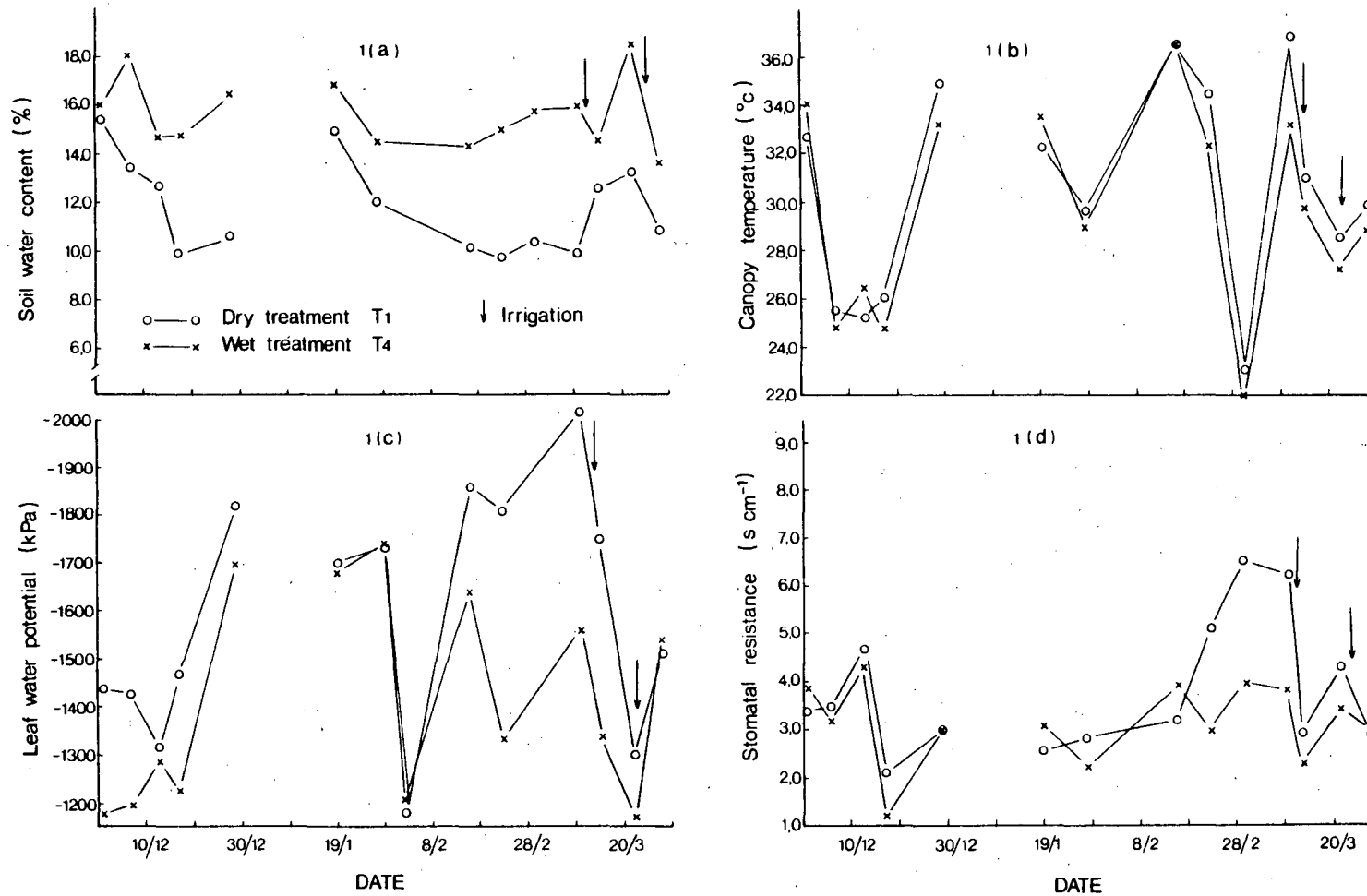
Fig. 1: Variation of soil water content (mass %) and plant parameters of water stress in
Colombar grapevines at 14h00 on a dry treatment plot (T1) and a well-watered control
(T4) during different drying cycles.
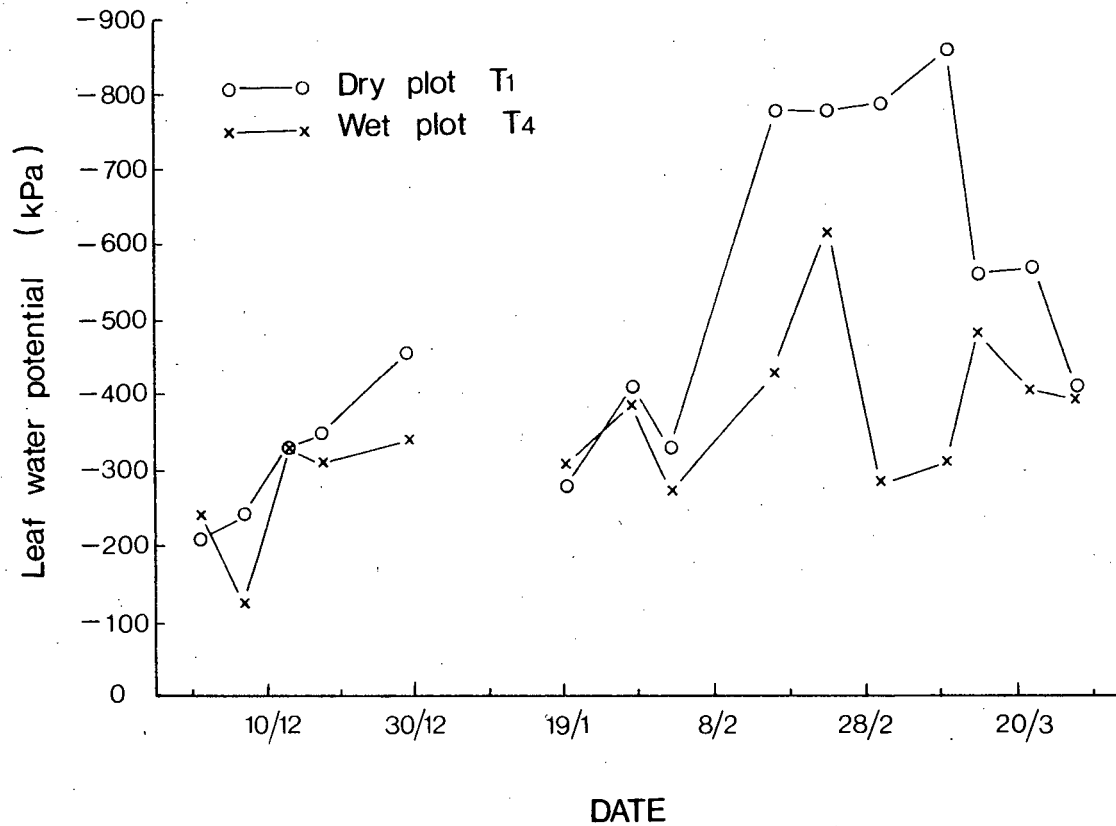
Fig. 2: Pre-dawn leaf water potentials of Colombar grapevines as
determined during different drying cycles.
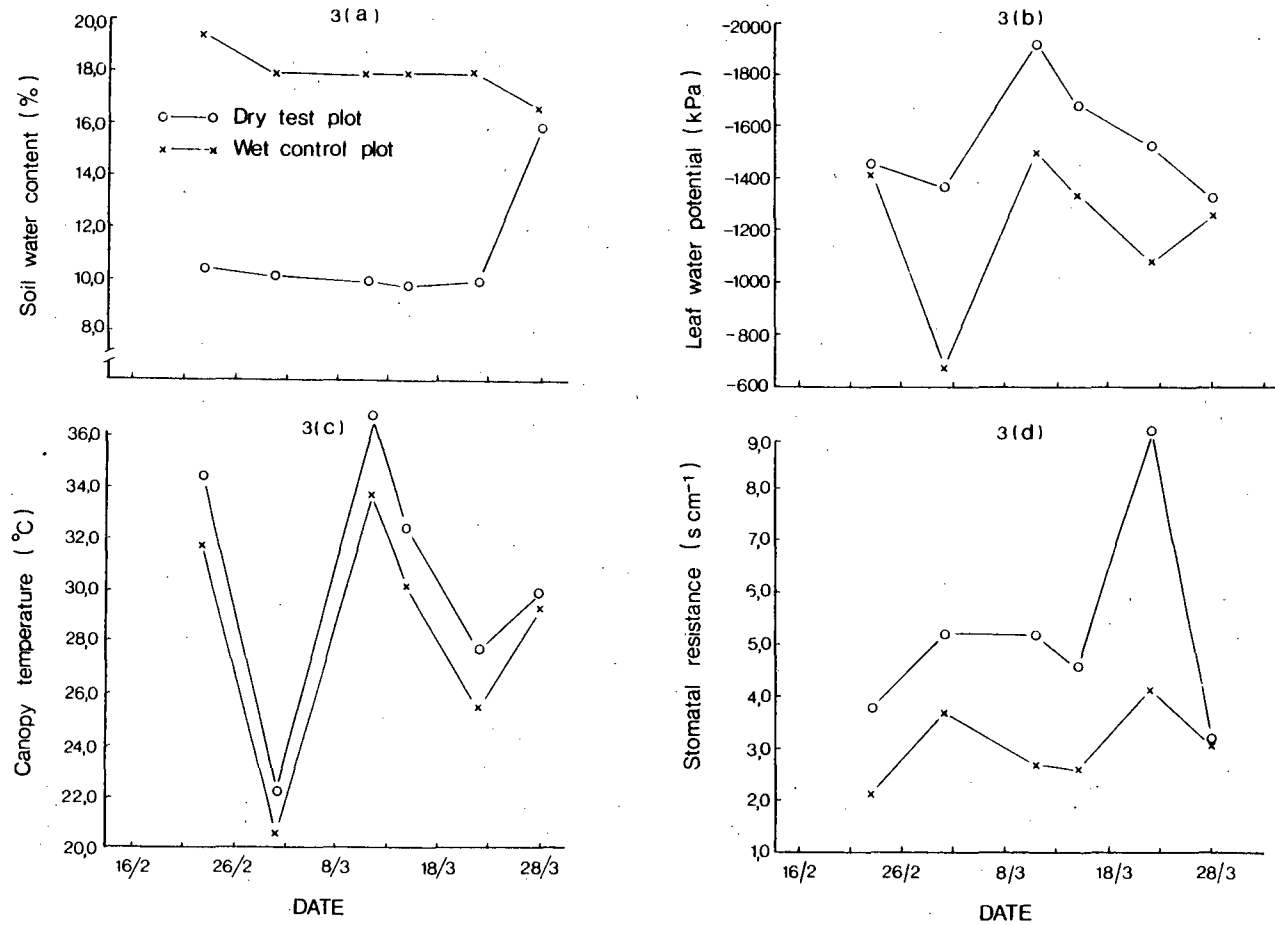
Fig. 3:   Variation in soil water content and plant parameters of water stress
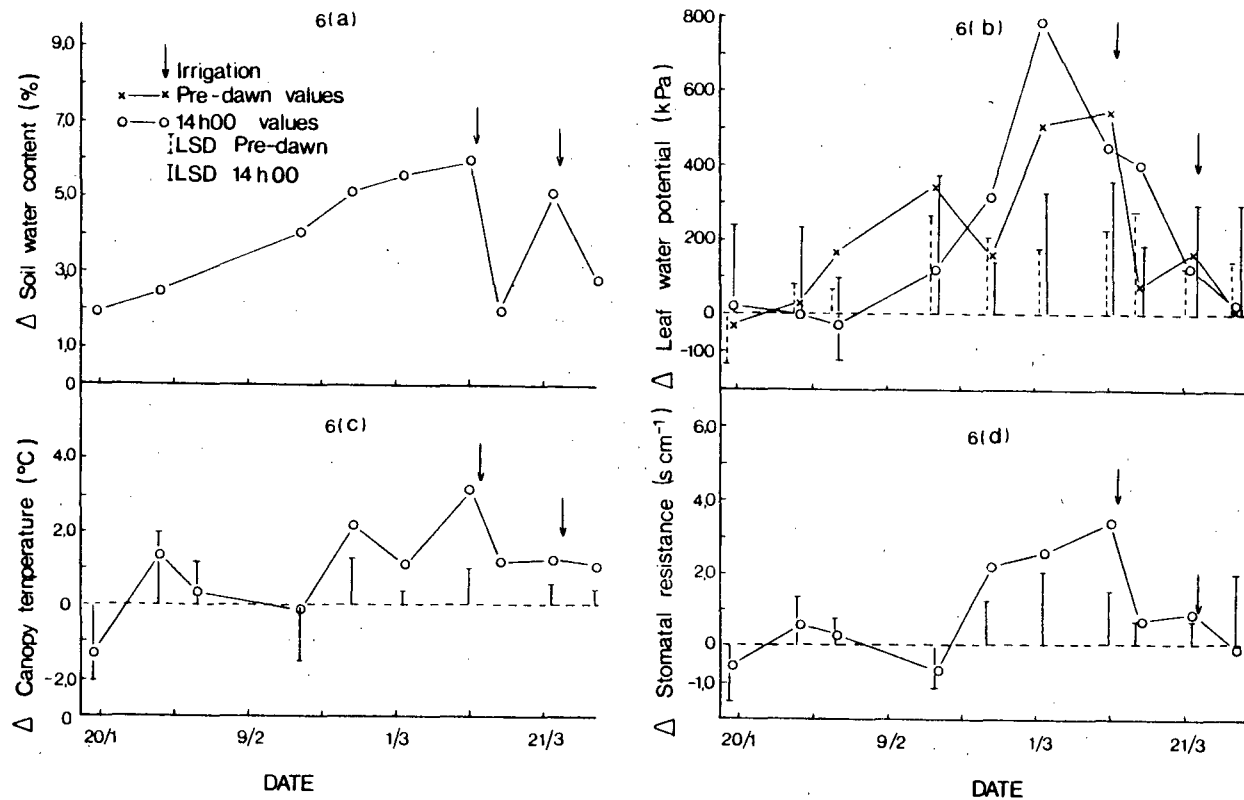   in Colombar grapevines on a trickle-irrigated control and a dry test
          plot.
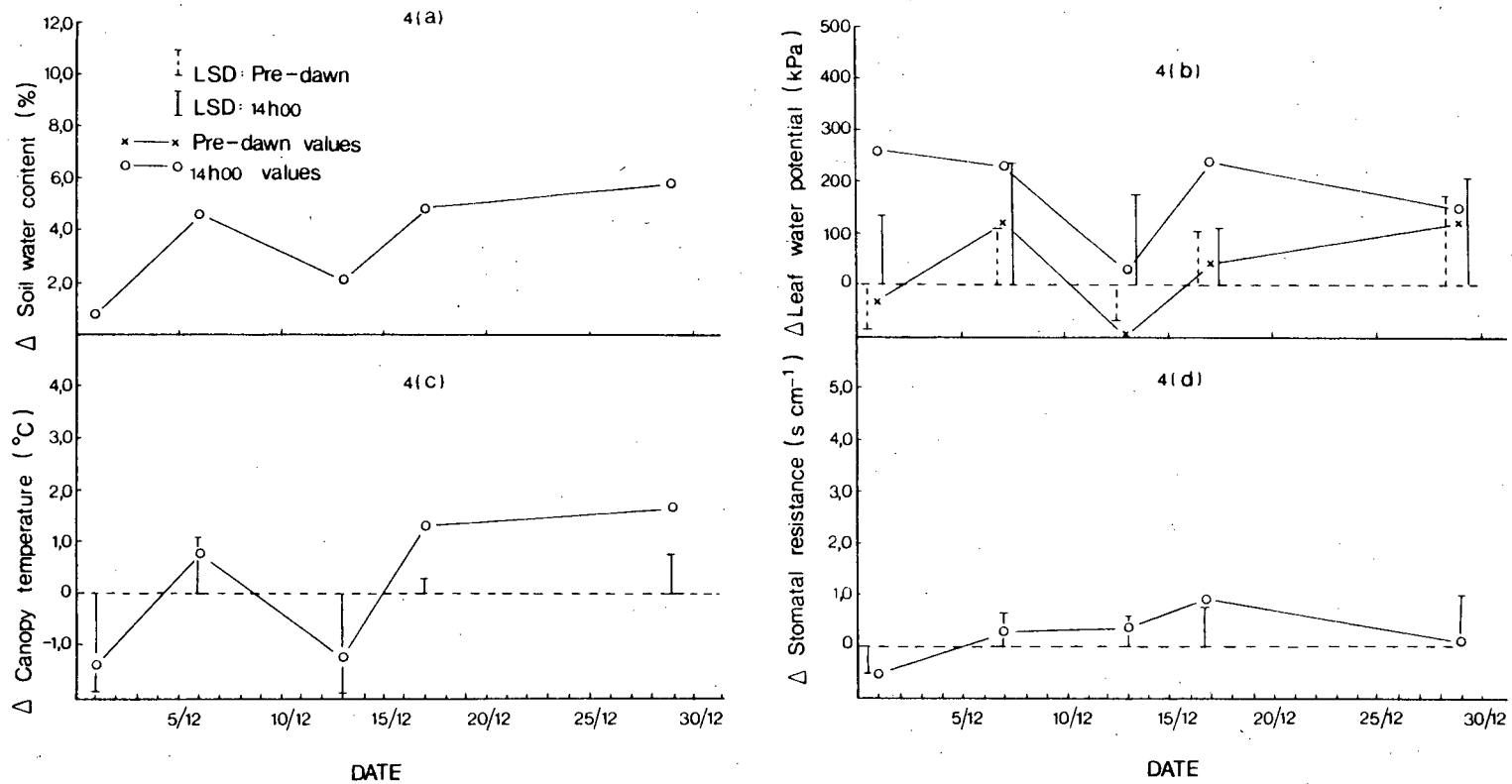
Fig. 4:   Soil water content (mass %) and plant parameter differentials ($\triangle$) determined on
Colombar grapevines in Experiment 1 during December 1982.
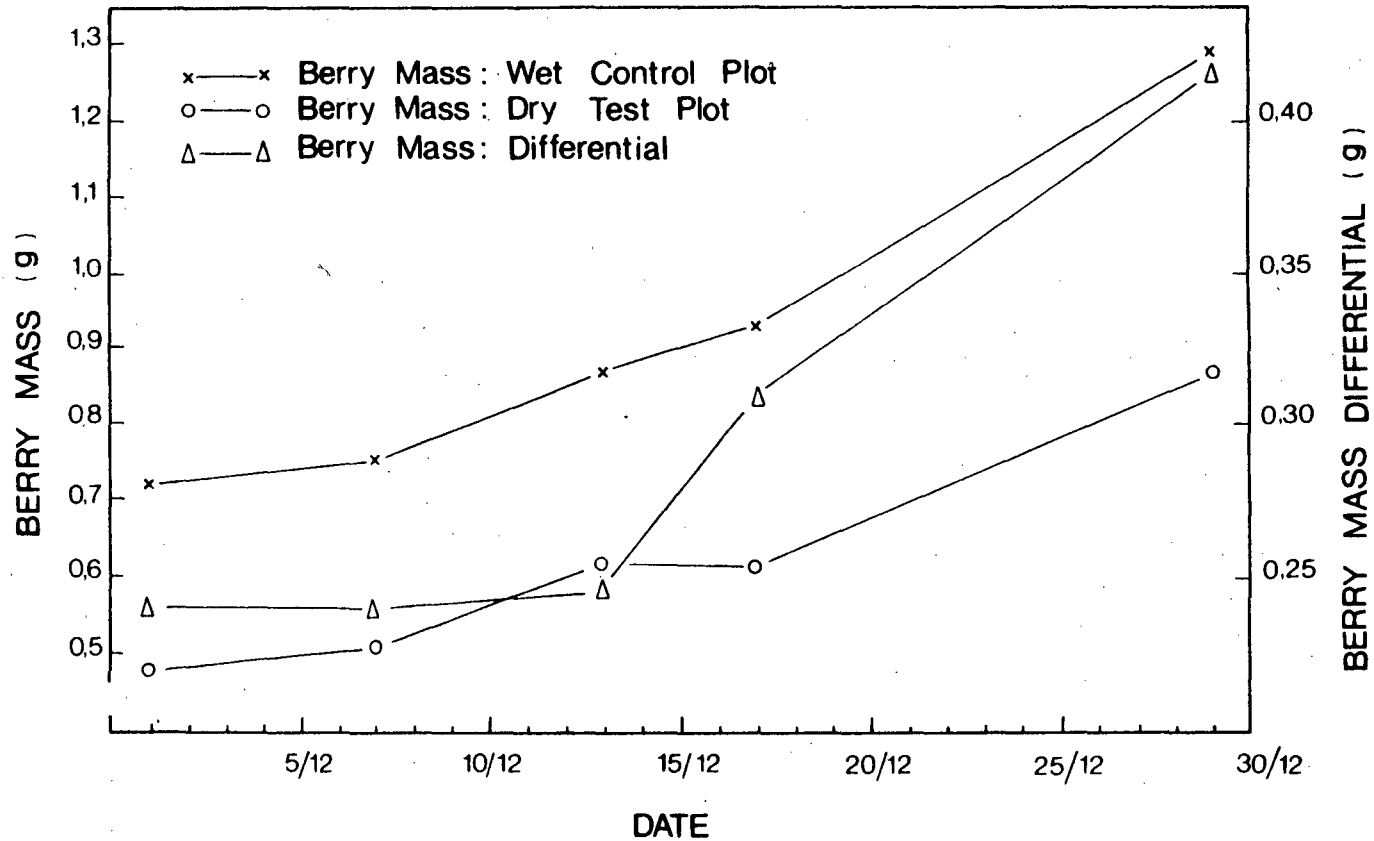
Fig. 5: Berry growth curves for Colombar on a control plot as well as on a
dry test plot during Experiment 1 in December 1982.

Fig. 6: Soil water content and plant parameter differentials ($\triangle$) determined on Colombar grapevines in Experiment 2 during January – March 1983.
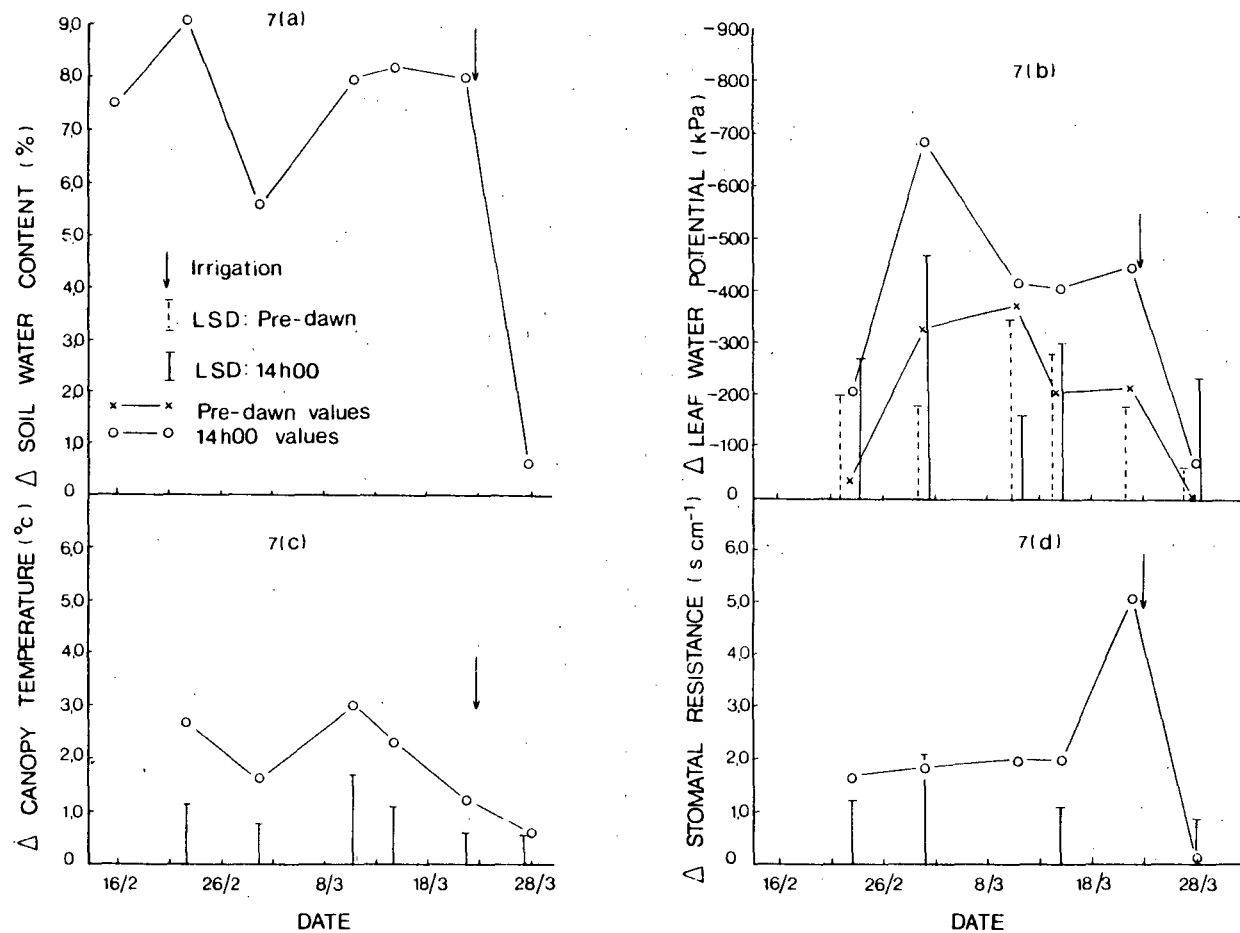
Fig. 7: Soil water content (mass %) and plant parameter differentials ($\triangle$) determined in Experiment 3 on trickle-irrigated grapevines.
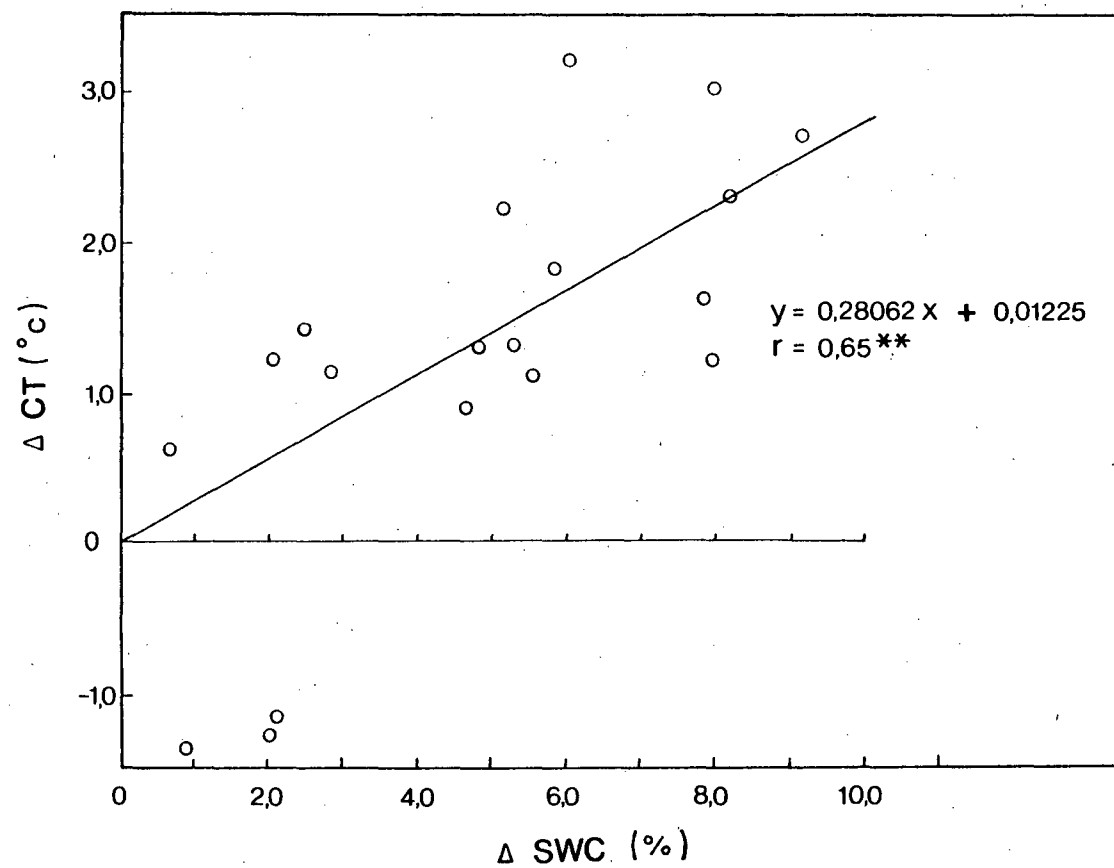
Fig. 8: Linear relationship between differentials ($\triangle$) of canopy tempe-
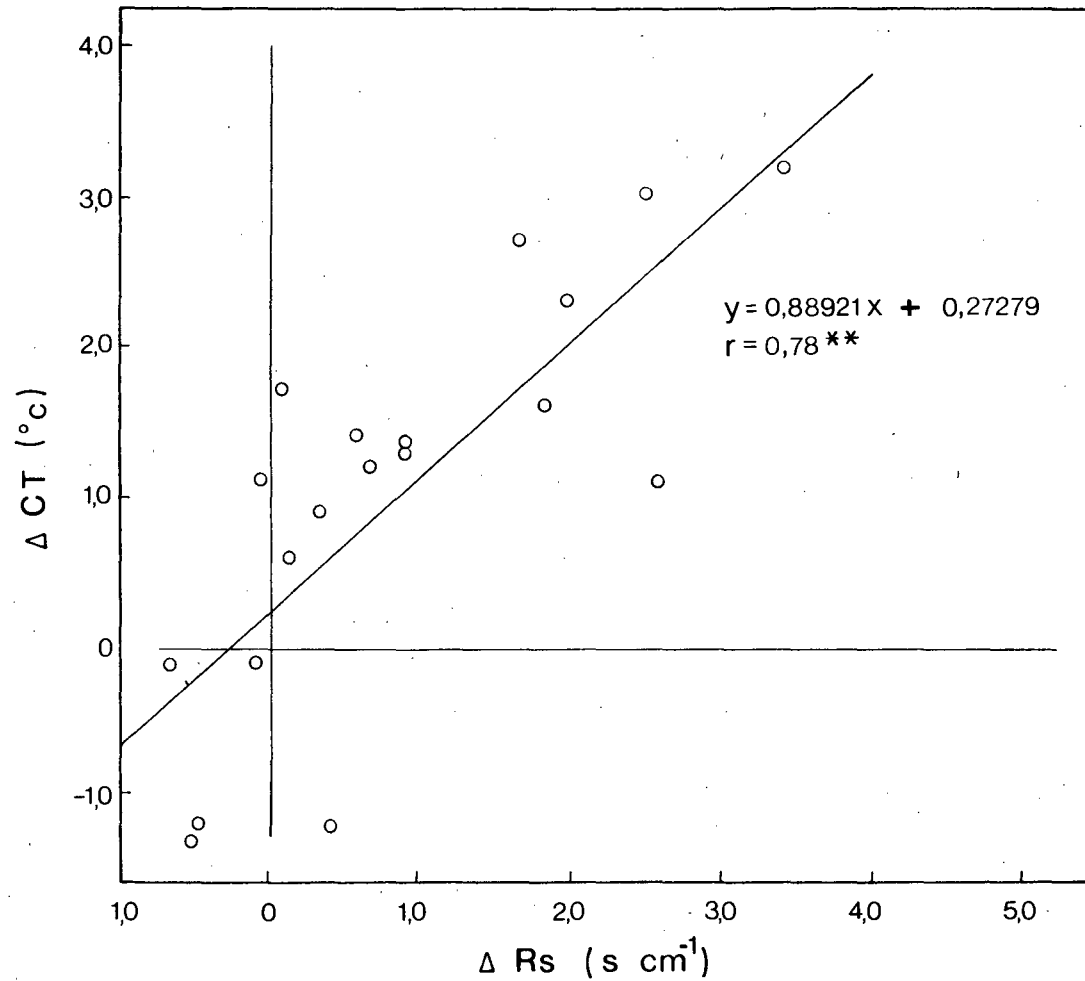rature (CT) and soil water content (SWC in mass %) in a Colom-
bar vineyard.

Fig. 9: Linear relationship between differentials (△) of canopy temperature (CT) and stomatal resistance (Rs) determined in a Colombar vineyard.

CHAPTER 8

CONCLUSIONS

1.   Parameters of plant growth viz., shoot length, berry size and mass as well as trunk circumference proved to be the most sensitive indicators of vine water stress.

2.   Shoot elongation rates started to decrease at high soil water potentials (SWP) and stopped between -60 and -80 kPa in pots. In another pot experiment shoot lengths were significantly greater at a SWP of -5 kPa than at -20 kPa while, in a field trial the shoot elongation rate and pruning mass were negatively affected at a 25% soil water regime compared to the much wetter 70% and 90% soil water regimes.

3.   Trunk circumferences of potted vines as well as in the vineyard significantly responded to soil water regimes. Trunks decreased in thickness when the SWP decreased from -5 kPa to -20 kPa in pots. In a vineyard a 25% soil water regime resulted in a decrease in trunk diameter in comparison with the two wettest regimes (70% and 90%). Soil water depletion to the 50% level assumed an intermediate position between the drier and the two wetter water regimes (but not significantly different from them) with regard to both pruning mass and trunk circumference. Trunks also showed a distinct period of growth which ended at véraison. Indications were that vine trunk circumferences decreased during ripening of the grapes, irrespective of irrigation treatment.

4.   During the period of cell division in the berry i.e. from end of flowering until 4 - 5 weeks later, berry growth was very sensitive to

water stress. In a pot experiment berry size decreased when the SWP decreased from -5 kPa to -25 kPa. Berry size was detrimentally affected at a 25% soil water regime in an experimental vineyard. High soil water regimes before flowering and after phase I of berry growth, could not prevent the reduction of berry size by water stress during this particular phase. This finding corroborated results of previous research. Water stress (25% regime) during the long and hot ripening stage also deleteriously affected grape yield. In contrast, no yield reduction was found by withholding water applications between bud burst and fruit set.

5. Cumulative grape yields obtained over a six year period in the experimental vineyard, showed a significant decrease in production at a 25% soil water regime compared to the 70% and 90% regimes. The cumulative yield difference between the dry treatment and the treatment which resulted in the highest yield (70% regime) amounted to 43,6 t ha^{-1}. These results clearly demonstrated that grape yields were not affected by decreasing the water regime from 90% to 70%. Even at a 50% regime, the grape yield was only slightly (not significantly) reduced. Consequently it can be concluded that sophisticated irrigation systems operating at high frequencies of water application, will not necessarily result in higher grape yields than irrigation systems which maintain the soil water regime at 70% or even at 50% on deep high potential soils.

6. Root growth studied in situ in root chambers in the vineyard displayed two distinct peaks of growth i.e. in spring and during the post-harvest period. In mid-summer, root growth was low and water uptake apparently occurred mainly through mature roots. Indications were that factors other than crop removal alone stimulated root growth in autumn. Root mapping by the profile wall method revealed a very uniform root

distribution with soil depth. In the case of tricklers the majority of roots was confined to the wetted zone, but roots outside this wet area remained alive and extracted water from the soil after spring rains.

7. Quality parameters in grape juice and must were affected by the irrigation treatments. In pot experiments the sugar concentration decreased with decreasing soil water potential, but the opposite was true in the vineyard. The driest treatments (25% soil water regimes during both the entire season and the ripening period only) together with tricklers, yielded the highest sugar concentrations and the lowest total titratable acidity (TTA). Frequent irrigations increased the TTA, and analyses of berry samples showed malic acid to be the most affected. Tartaric acid reached the highest values in dry treatments at véraison, but differences among treatments disappeared towards harvesting. Chenin blanc was more sensitive to soil water regimes than Colombar as regards quality parameters although the general tendency was the same in both cultivars. The wet 90% and 70% soil water regimes gave rise to lower sugar concentrations and higher TTA than the 50% and 25% regimes. Wine quality of Colombar as determined by a tasting panel did not differ among irrigation treatments.

8. The irrigation systems did not differ with regard to vine performance, but between 25% - 30% of water was saved by using trickle irrigation in comparison to flood, sprinklers and micro-jets. Only 414 mm of irrigation water per season was applied by tricklers compared to 580 mm used by the other irrigation systems. This result stresses the fact that management and soil water regimes are more important to vine response than the irrigation system itself. Trickle irrigation required a high application frequency of one irrigation every two days to maintain a 90% regime in the relatively small soil reservoir (width of wet

strip = 1 m). Two micro-jet irrigations per week were adequate to maintain a 90% soil water regime, while an irrigation cycle of 16 - 21 days kept the experimental vineyard at the conventional 50% regime.

9. Trickle irrigation produced a more favourable sugar/acid ratio in the must than the other irrigation systems. This improved quality might be linked to poorer shoot growth, a positive factor on the high potential soil.

10. Mild water stress during ripening by irrigating the upper part of the soil profile only and allowing water depletion in the deeper root zone proved to be a most successful treatment. Although no improvement in must quality was found, grape yield remained unaffected while saving 44% - 53% of the water needed from vérsaison to harvesting by fully irrigated treatments.

11. With the exception of trickle irrigation, crop factors were similar for irrigation systems as well as for the 50%, 70% and 90% regimes. The crop factors increased sharply from October to November, after which no distinct peaks of water consumption occurred until harvesting. Maximum values of 0,49 were reached during January and February. For the late ripening cultivar Colombar, the crop factor was still 0,48 during March compared to 0,30 recommended to date. In general, crop factors determined in this study were 20% higher than those presently in use for wine grapes. Crop factors for trickle irrigated wine grapes were calculated for the first time in South Africa. With an average value of 0,33, these factors were significantly lower than those for other irrigation systems.

12. A study of plant physiological parameters of water stress showed large diurnal fluctuations. High stomatal resistance (Rs) in stressed vines and maximum leaf temperature (Tl) as well as minimum leaf water poten-

tials (LWP) values were generally found between 14h00 and 15h00. Leaf exposure affected the plant parameters significantly. Leaf water potential and Rs were respectively 20% and 53% higher on shaded than on fully sunlit leaves. Water potential gradients existed between leaves and bunches. Although pre-dawn water potential was lower in bunches than in the leaves, bunch water potential decreased at a slower rate during the day and reached a minimum value which was both higher and later in the day than that attained by leaves. Plant water redistribution was postulated as a result of these gradients.

13. The diurnal variation of LWP on most days was best explained by Tl. Considering the entire period from véraison to harvesting, linear regression analysis of plant and environmental variables showed that both SWP and pre-dawn LWP in conjunction with the relative humidity, significantly contributed to the variation in LWP at 14h00. A curvilinear relationship was found between Rs and LWP. The stomata remained open in the vineyard until a threshold LWP of -1 600 kPa was reached after which Rs values rose rapidly. In a glasshouse study a LWP threshold value of -1 000 kPa was sufficient to cause stomatal closing.

14. Considered over the ripening period, photosynthetic activity (PA) correlated poorly with the other plant and environmental variables due to a large coefficient of variance in PA. However, PA commenced to decrease at the same early stage indicated by pre-dawn LWP during a drying cycle. The diurnal fluctuation in PA correlated best with photosynthetic active radiation (PAR). Under stressed conditions changes in Rs explained PA fluctuations best ($R^2 = 0,71$).

15. Canopy temperature measured with an infra-red thermometer was applied successfully to indicate water stress in grapevines due to the high

accuracy of the instrument and the small standard deviation among replicates. Maximum temperature differences between stressed and well-watered control plots were 3,2 °C. Canopy temperature differentials were significantly, positively and linearly correlated with both $\triangle$ SWC and $\triangle$ Rs. Perusal of results suggested the timing of irrigations at a $\triangle$ CT range of 2,6°C - 1,2°C.

16. Pre-dawn LWP proved to be the best physiological indicator of vine water stress in the present investigation. Pre-dawn LWP, which was correlated significantly with both SWC (R= -0,89) and SWP (R = 0,95) fixed the onset of vine water stress at a soil water potential of -64 kPa. Canopy temperature measured by the infra-red thermometer fell into the same category of sensitivity as LWP_{14} and Rs with regard to indicating the onset of water stress.