

WATER RELATIONS OF VITIS VINIFERA L.

c.v. 'CABERNET SAUVIGNON'

by

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A Thesis Submitted to the Faculty of the

DEPARTMENT OF PLANT SCIENCES

In Partial Fulfillment of the Requirements  
For the Degree of

MASTER OF SCIENCE  
WITH A MAJOR IN HORTICULTURE

In the Graduate College

THE UNIVERSITY OF ARIZONA

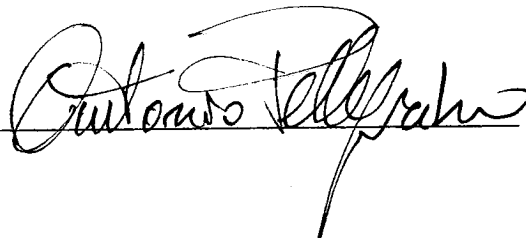
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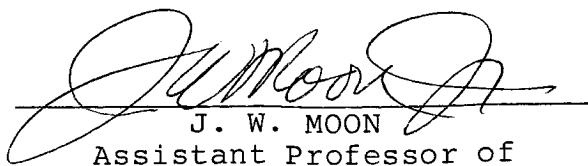
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## ACKNOWLEDGMENTS

This study was supported in part by the United States Department of Agriculture Anti-Desertification Grant. Assistance for data collection and technical support was provided by Mrs. Nancy Ferguson and Mr. Larry Kasperson. Project leaders were Dr. John Moon and Dr. Allan Matthias, who offered ongoing guidance and supervision. Special thanks are offered to Dr. Gordon Dutt and Mr. Awadis Arslan for their numerous cooperative efforts.

The greatest support was provided by my wife Lorraine, to whom I dedicate this work.

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## ABSTRACT

Evapotranspiration measured from two Vitis vinifera L. c.v. 'Cabernet Sauvignon' by the water budget method totaled  $136.1 \text{ l d}^{-1}$ , and steady state leaf transpiration rates averaged  $57 \pm 47 \text{ mg m}^{-2}\text{s}^{-1}$  from March to August 1986 in Oracle, Arizona. Rooted cuttings were subjected to four levels of water stress in the greenhouse by withholding water. Pot weight variation was correlated to soil water potential by thermocouple psychrometry. Mesophyll conductance and  $\text{CO}_2$  assimilation, measured with an open gas exchange system, were decreased by 80 and 70%, respectively, indicating severe limitations imposed by water stress on photosynthesis for this cultivar.

## CHAPTER 1

### INTRODUCTION

In the semi arid climate of Southeastern Arizona (Sonoran Desert), wine grape is becoming an important commercial crop due to its drought and salt tolerance (Ayers and Westcot, 1985). In particular, a combination of a favorable climate, and a particular soil type, contribute to make some fine table wines (Mielke et al., 1980). Limited knowledge is available on water use by grapes grown on salt treated catchments and the effect of water stress on photosynthesis for most wine grape cultivars.

In the Sonoran Desert, a serious concern for both water conservation and land reclamation have led scientific investigators to evaluate the relationship between crop production and consumptive water use. Information on crop consumptive use on unique salt treated catchments, however, is scarce. Estimating consumptive use on runoff-catchment systems is further complicated by the low density plantings of perennial crops that are employed to conserve total water use. Numerous factors determine crop water use, ranging from climate, soil type, topography, genetics, and cultural practices. Efficient irrigation management programs should be based on the actual crop consumptive use (Erie et al.,



1965; Doorenbos and Pruitt, 1977). Irrigation scheduling that replenishes soil moisture at a predetermined consumptive use threshold will in most cases keep plants in an optimal productive environment with the most efficient use of water resources.

The crop consumptive water use, or simply evapotranspiration (ET), refers to the "unit amount of water used on a given area in transpiration, plant growth and evaporation from adjacent soil" (Erie et al., 1965). The ability to estimate ET without costly and time consuming direct measurements is of great interest to many, from the grower to the researcher. Numerous models predicting ET have been developed; however, their divergence in predicting ET increases when used in the extreme climatic conditions found in arid and semi-arid regions of the world. Most methods available for estimation of ET, with the exception of the water budget, are not adequate for low density plantings.

The objective of the first part of this study was to measure ET of Vitis vinifera L. c.v. 'Cabernet Sauvignon' utilizing a water balance method for estimating consumptive use. Additionally, leaf transpiration rates and leaf conductance to water vapor were monitored in the field both before and after irrigation to determine the degree of water stress.

Little information can be found on the effect of water stress on carboxylation efficiency for wine grape cultivars, and significant varietal differences are to be expected in relation to drought tolerance (Reuther, 1983).

The objective of the second part of this study was to determine the gas exchange characteristics of greenhouse grown Vitis vinifera L. c.v. 'Cabernet Sauvignon' under differential regimes of water stress through the analysis of the CO<sub>2</sub> concentration at the mesophyll cell surface [CO<sub>2</sub>]<sub>I</sub> and the CO<sub>2</sub> assimilation rate (A). Slopes of A versus [CO<sub>2</sub>]<sub>I</sub> curves were analyzed to assess the effect of soil moisture stress on g'<sub>m</sub>.

## CHAPTER 2

### LITERATURE REVIEW

Numerous models predicting ET have been evaluated, requiring measurements ranging from simple free water evaporation (Penman, 1948), to more sophisticated satellite imagery (Powell et al., 1984), and remote sensing (Idso et al., 1977). However, most research on the consumptive use of wine grapes has centered on estimates made from the class-A pan evaporation method (Smart et al., 1974; Doorenbos and Pruitt, 1977; Freeman et al., 1979; Van Zyl and Van Huyssteen, 1980; Klein, 1983). For this reason, the class-A pan method will be briefly discussed here, although the objectives of the study were limited to determine specific seasonal ET variations of 'Cabernet Sauvignon' by the water budget method without any attempt to relate these data to pan evaporation.

Crop ET ( $ET_C$ ) is usually estimated indirectly by relating reference ET ( $ET_O$ ) to the specific crop coefficient ( $K_C$ ) as defined by the equation:

$$ET_C = k_C \times ET_O \quad (1)$$

Reference ET constitutes ET as measured from a crop of uniform stand and a cover crop such as grass or alfalfa, while

$k_C$  represents an adjustment factor to account for specific crop, cultural and environmental variables (Doorenbos and Pruitt, 1977). Both  $ET_0$  and  $k_C$  are generally modeled in relation to meteorological factors to allow for fast ET calculations from basic weather data. Values of  $k_C$  for grapes have been obtained by measurements of soil moisture depletion ( $E_t$ ) by the neutron scattering method (Van Zyl and Van Huyssteen, 1980) or by soil water potential measurements (Klein, 1983) and related to free water evaporation ( $E_0$ ) by the equation:

$$k_C = E_t/E_0 \quad (2)$$

The overall seasonal ET modeled by pan evaporation are therefore based on Eq. 1. While  $k_C$  determinations by pan evaporation have been reliable for many annual crops, they have proven to be inadequate for perennial fruit crops like grapes (Klein, 1983). Indeed,  $k_C$  adjustments are needed during both the growing season and in successive years to account for changes in canopy development (Klein, 1983). In the orchard, care should be taken in expressing  $k_C$  on a per tree basis if drip irrigated or on a per hectare basis if flood or sprinkler irrigated. Renquist (1987) commented on water consumption of apple trees as small as 3% of  $ET_0$  if calculated on a tree basis or a  $k_C$  of 0.03 if referred to irrigation of the whole orchard area. Similar ambiguities

are common in studies of wine grape ET. Van Zyl and Van Huyssteen (1980) reported conflicting data for  $k_c$  values for bush grown grapes when calculated solely by relation to pan evaporation. They concluded that in conditions of very dry surface soil, as found in South Africa, no correlation could be found between ET and pan evaporation, whereas they found decreasing ET rates coupled with canopy development, which was due to significantly different microclimates found within the different canopies tested. In addition, the  $k_c$  values did not increase from bud break to leaf drop as expected, but decreased as evaporative demand increased throughout the season due, mostly to full canopy development and growth cessation. For this reason, the  $k_c$  values reported in the study of Van Zyl and Van Huyssteen (1980) are among the lowest found, which suggested that grapes are low in their seasonal water requirements.

Another method of estimating ET which is not without problems is the use of the water budget method, which utilizes a neutron scattering probe for soil water measurement. The use of the water balance equation, which simply describes the mass conservation of a hydrologic system, enables the estimation of small changes in soil water content due primarily to ET (McGowan and Williams, 1980). Some researchers admit that assessment of errors related to this method can be too large to provide reliable ET evaluations (Hanson and

Dawdy, 1976). Others believe that this method cannot accurately estimate daily ET without large errors, although it can be a relatively quick, easy and economical method (Rouse and Wilson, 1971). Since measurements are taken always in the same place, the resulting differences in change of soil water storage are not confused with the soil variability (McGowan and Williams, 1980). However, since the total measurement error of the neutron scattering technique is based on the total number of observations made, neutron meter sensitivity may drift in time and cause considerable bias, capable of producing ET determinations constantly above or below the real values. Also, total measurement error is not related only to crop ET, but to the entire amount of water moving within the volume of soil under study (Hanson and Dawdy, 1976). Accuracy of this method can be gained by increasing the time interval between successive measurements. It has been proposed that in situations of high ET and no precipitation, a reasonable accuracy can be achieved with 6 sites monitored at a 4-day time span, and that this interval of time needs to be extended to 17 days to maintain an error within 10% when only 1 site is employed or when ET is high and precipitation frequent (Rouse and Wilson, 1971). Other criticism of the neutron probe scattering technique have been suggested by Van Bavel et al. (1968a, b), who discussed limitations due to deep soil water seepage and soil variability.

However, the assumption of negligible seepage can be made with the least error in situations of very low precipitation and infrequent irrigation. Conversely, if irrigations took place and seepage was ignored, an overestimation of ET by 15 to 30% is likely to be found (McGowan and Williams, 1980). Finally, the assumption of negligible seepage can be made with little error when monitoring a soil profile of 2.5 m or deeper (Doorenbos and Pruitt, 1977).

Compared to other woody deciduous fruit crops, grapes have long been recognized as drought tolerant (Smart and Coombe, 1983). However, terminal shoot length and leaf area were found to be very sensitive to water stress (Smart et al., 1974; Carbonneau and Casteran, 1979). Similarly, yield changes due to irrigation were reported as high as 131% (Smart and Coombe, 1983). Many factors contribute to grapevine drought tolerance. There may also be a greater degree of stomatal resistance ( $r_s$ ) to vapor loss in grapes as compared to other crops (Doorenbos and Pruitt, 1977). Stomatal resistance increased under increasing water stress in 'Shiraz' and 'Concord' vines, and maximum stomatal closure was observed at leaf water potentials of -1.3 and -1.6 MPa, respectively (Smart and Coombe, 1983).

The adverse consequences of water stress on photosynthesis have been well documented for most crops, while uncertainties have arisen when attempting the separation of

stomatal from non-stomatal effects (Woolhouse, 1983). Simply, the effects of water stress on photosynthesis can be summarized as a direct inhibition of the various biochemical processes involved in carbon metabolism, and an indirect reduction in CO<sub>2</sub> uptake caused by stomatal closure (Baker and Musgrave, 1964).

In order to calculate both the stomatal ( $g_1$ ) and the non-stomatal ( $g'_m$ ) response to water stress, simultaneous determinations of water vapor and CO<sub>2</sub> fluxes must be taken, respectively, as a function of the leaf intercellular CO<sub>2</sub> concentrations ( $[CO_2]_I$ ). Several contradictions can be found on this subject, due primarily to different methodologies employed. For example, if water stress is imposed rapidly,  $g_1$  alone was observed to decrease first, while both  $g_1$  and  $g'_m$  can be found to decrease concurrently when more gradual rates of stress were imposed (Woolhouse, 1983).

This review will consider the water potential, the stomatal conductance and the non-stomatal limitations affecting photosynthesis under water stress.

#### Water Potential

Generally, a decrease in soil water potential causes a loss of turgor, which in turn causes stomatal closure and thus a reduction in net photosynthesis. It has been argued that the stomatal conductance ( $g_1$ ) can be more closely related to the soil ( $\psi_{soil}$ ) rather than to the leaf ( $\psi_l$ )



water potential (Gallan et al., 1986). Especially for perennial fruit crops, the relationship between water potential ( $\psi_1$ ) and transpiration rate (TR) is quite relevant. In particular, while the turgor component ( $\psi_p$ ) of  $\psi_1$  is the most reliable indicator of plant water stress, it is often calculated by difference of  $\psi_1$  and osmotic potential ( $\psi_s$ ) (Lakso, 1985). It appears, therefore, that the ideal drought tolerant plant should be capable of maintaining full turgor even at decreasing  $\psi_1$  and possess a small but elastic cell volume (During, 1985). Indeed, grapes have been found to display under mild water stress a reversible mid-day stomatal closure (mid-day depression), sometimes persisting even after TR rates have dropped, indicating a "feedforward" response mode to high VPD (Lakso, 1985). Furthermore, in situations of slow development of water stress and "retention of maximum fluorescence yield," grapes maintain turgor through osmotic adjustment (Downton, 1983). This mechanism would prevent damages to photosystem II normally occurring under water stress. Additionally, Downton (1983) observed that plants undergoing water stress experience increased fluorescence similar to those of well irrigated plants growing under supraoptimal light conditions (photoinhibition). Lakso (1985) has indicated that adjustments in  $\psi_s$  in fruit trees and grapevines are common physiological responses to water stress. If  $\psi_s$  does not change,  $\psi_p$  has to be directly related

to  $\psi_1$  during water stress, suggesting a "passive osmotic adjustment" due to water loss and subsequent solute accumulation. During (1985) found that in grape leaves which had lower  $\psi_s$  under water stress that the osmotic adjustment was associated with a decrease in starch and an increase in glucose and fructose. This adjustment, however, was dependent on the cultivar and on the stress intensity and duration.

The mid-day depression in  $\psi_1$  found in grapes seemed to be largely dependent on the relative water content (Lakso, 1985); therefore, determinations of water loss from full to zero turgor (During, 1986) could be of particular interest because they take into account the osmotic adjustments. This method, which has been used in Germany to test drought resistance of more than 17 grape cultivars, employs measurements of  $\psi_1$  and water loss at full hydration (maximum  $\psi_p$ ) and at full wilting (zero  $\psi_p$ ), thus allowing the determination of a "bulk modulus of elasticity" of leaf tissue. A high elasticity indicated a cultivar well suited for drought tolerance by allowing adequate turgor maintenance, even at decreasing  $\psi_1$ .

#### Stomatal Conductance

The active role of  $g_1$  on photosynthesis under limiting water availability can be clearly found in gas exchange studies, where increasing sensitivity of  $g_1$  to  $CO_2$  was directly related to increasing levels of water stress (Bunce, 1981; Jones and Fanjul, 1983; Loveys, 1984a; Lakso, 1985;

Flore et al., 1985). In fact, in unstressed apples,  $g_1$  did not appear to respond to increasing  $CO_2$  concentration; however, under low  $\psi_1$ ,  $g_1$  was found to be in tight relationship with  $CO_2$  assimilation (A), which in turn allowed higher water use efficiency (Flore et al., 1985). Several investigators have reported a direct linear relationship between A and  $g_1$ , (Bunce, 1981; Loveys, 1984a; Yoshie, 1986), whereas Jones and Fanjul (1983) proposed that this relationship was linear only at  $g_1$  values below  $0.2 \text{ cms}^{-1}$ . Above this value,  $g_1$  was found to respond mainly to increasing VPD. This reasoning suggested therefore that  $g_1$ , and in particular TR in fruit crops were regulated by VPD. In plants conditioned under mild water stress,  $g_1$  was primarily controlled by  $[CO_2]_I$  and thus the limiting factor to A was  $[CO_2]_I$ . However, as stress progressed,  $g_1$  sensitivity to  $[CO_2]_I$  increased, posing a second boundary (VPD boundary) to A in which the limiting factor was the vapor pressure gradient. At the same time, as  $g_1$  responded to stress by reducing transpiration per unit of VPD, thus maintaining constant  $[CO_2]_I$ , which resulted in a significantly higher water use efficiency (Lakso, 1985). Under conditions of advanced water stress, and especially of high VPD, a constant and low transpiration rate in apples and in grapes is, therefore, to be expected as a preventive mechanism to maintain a positive carbon balance and the

dissipation of energy charge to prevent photodestruction of chlorophyll.

At the onset of water stress, physiological changes in the leaf mesophyll must take place in order to couple  $g_1$  with  $[CO_2]_I$ . Loveys (1984a) reported that mid-day grapevine depression in  $\psi_1$  was associated with leaf accumulations in Abscisic Acid (ABA), which might have been responsible for partial stomatal closure. It has been debated whether increases in ABA, acting independently of the leaf water status, could regulate stomatal conductance (Gallan et al., 1986; Loveys, 1984a, 1984b; Lakso, 1985; Flore et al., 1985). Later, it seemed that under low water stress,  $g_1$  would be insensitive to  $[CO_2]_I$ , probably due to low levels of ABA. However, as plant water stress increased, high concentrations of ABA could induce a sensitivity of  $g_1$  to  $[CO_2]_I$  (Lakso, 1985; Flore et al., 1985).

#### Non-Stomatal Limitations

Clearly, the indirect stomatal effect in response to water stress has long been considered as a major limitation to photosynthesis and therefore is the single plant response most often measured. However, theoretical models presented by Farquhar and Sharkey (1982) suggested that stomatal conductance limitations to photosynthesis had generally been overestimated, and that stomatal limitations would actually be minimal during advanced water stress. Matthews and Boyer

(1984) suggested that although stomatal closure occurs as a result of water stress, photosynthesis may be limited by the chloroplast capacity to fix  $\text{CO}_2$  rather than by the increased diffusive resistance. More recently, Ort and Boyer (1985) concluded that the main effect of water stress on photosynthesis was through the inhibition of photophosphorylation, causing a dramatic decline in quantum yield and a reduction of  $\text{CO}_2$  assimilation rate through the inhibition of photosystem II. Photosynthesis may also be negatively affected under water stress by a progressive impairment of enzymes of the carbon reduction cycle or turnover of the substrate (Begg et al., 1976).

Finally, mesophyll conductance ( $g'_m$ ) decreased as water stress increased, but independently of stomatal behavior. As a consequence, assimilation was reduced (Lakso, 1985). Very few studies, especially for wine grape cultivars, attempted a proper separation of stomatal and mesophyll limitations to water stress. In general,  $g'_m$  is expected to decrease to a lesser extent than  $g_1$ . The present study will not attempt a separation of the two, but will evaluate the slopes of the linear portion of the A versus  $[\text{CO}_2]_I$  curves to quantify the damage of water stress on the carboxylation efficiency of 'Cabernet Sauvignon'.

## CHAPTER 3

### MATERIALS AND METHODS

'Cabernet Sauvignon' grapes used in the first part of this study were planted in 1982 at the Oracle Agricultural Center, located about 50 Km north of Tucson, Arizona, at an elevation of 1121 m above mean sea level. These plants were grafted in 1982 onto Dogridge (Vitis champinie) rootstock, which produces a very vigorous root system resistant to soil borne fungal diseases. According to the availability of manpower, in the winter of 1986, two vigorous vines were chosen among 42 other plants growing in the same field, according to optimum yield history. Two border rows were allowed on both sides of the vines. The two plants selected were in the middle of the two inner rows. In order to determine the physical properties of the Whitehouse loam soil and to estimate plant rooting depth, a 3 m deep trench was selected about 50 m from the plants to avoid catchment damage. Visual observations were made for root distribution and pattern throughout the profile. Most of the fibrous root system was confined to the top 1.5 m of the profile. Examination of this root system showed a consistent taproot extending below 3 m with laterals extending at regular intervals up to 2 m from the vine. In addition, undisturbed

soil samples were collected for soil bulk density measurements (Table 1) and gravimetric moisture determinations. Plant spacing was 2.2 m and row spacing 9.4 m, which gives each plant an area of 20.68 m<sup>2</sup>. An effective rooting depth of 2.5 m was chosen based on observations from the excavation and gave an effective soil volume of 51.7 m<sup>3</sup> per plant (Fig. 1). Each site contained 8 neutron probe access tubes (Fig.1) for soil moisture determinations by a Troxler Moisture Meter (AM:BE mod. #1255). Each access tube (galvanized steel pipe 3 m long 5 cm in diameter) was driven into a hole manually drilled with an auger of smaller diameter. Soil samples were collected at 25 cm intervals while drilling the holes to determine the gravimetric moisture content. Later, moisture content was correlated to probe readings taken at the time of access tube installation for each interval of depth. Volumetric moisture content was then correlated to instrument count rate to produce two calibrations: one for the top 25 cm of soil (Fig. 2) and one for the rest of the profile (Fig. 3). Measurements of soil moisture content were started at bud break on March 14, 1986 (day 0) and continued at bi-weekly intervals until August 21, 1986 (day 168). ET was calculated by the water budget equation, with the assumption of negligible seepage below 2.5 m. The plot had been previously embanked to prevent

Table 1. Whitehouse loam soil bulk density variations by depth.

Depth (cm)	Density (g cm <sup>-3</sup> )	Depth (cm)	Density (g cm <sup>-3</sup> )
25	1.68	150	1.97
50	1.66	175	2.18
75	1.91	200	1.79
100	1.75	225	1.46
125	2.02	250	1.58



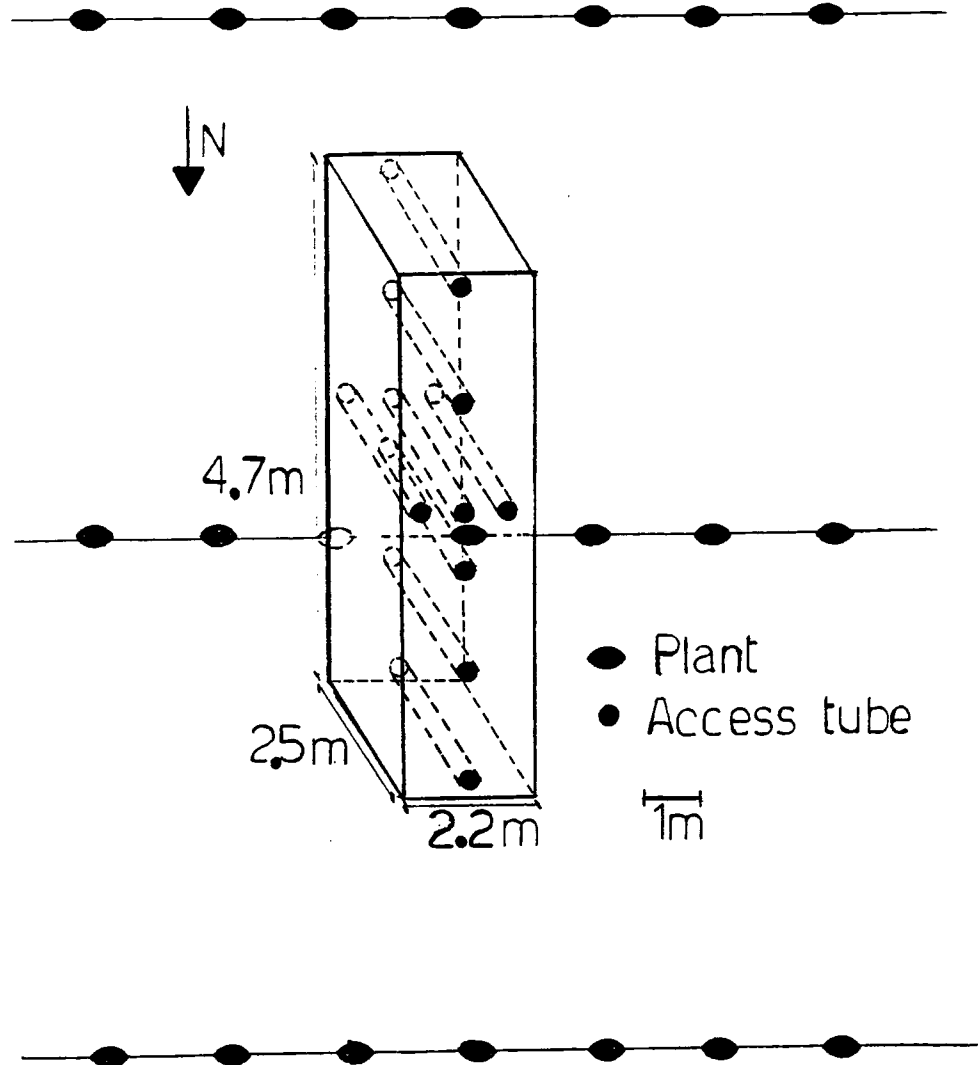


Fig. 1. Experiment design.

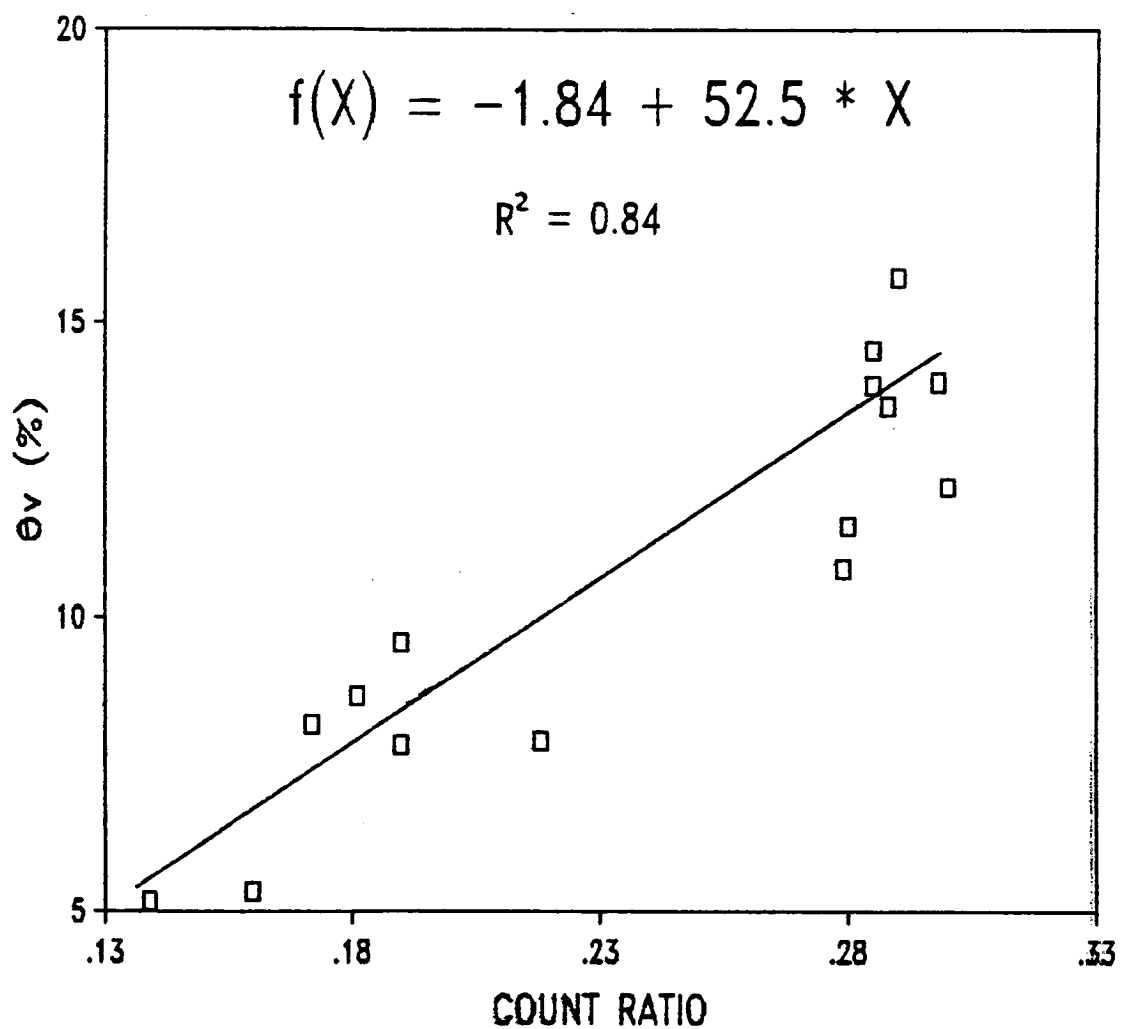


Fig. 2. Neutron probe calibration for the top 25 cm of soil.

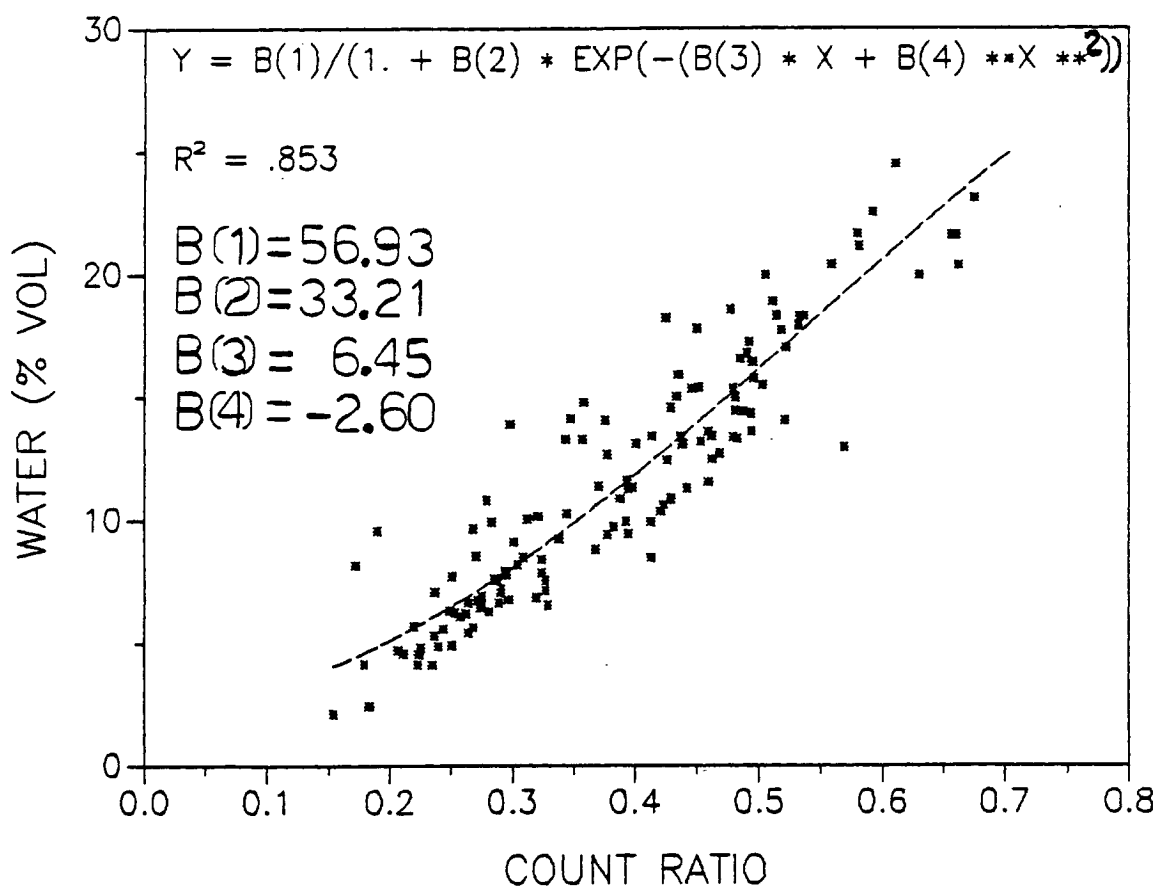


Fig. 3. Neutron probe calibration for soil depths 25 to 250 cm.

surface run on from adjacent fields. A simplified version of the equation was therefore employed:

$$(P + I) - Q - ET = \pm dS/dt$$

where P is the precipitation (mm), I the irrigation (mm), Q the plot runoff (mm), and dS/dt the rate of change in soil water storage (mm d<sup>-1</sup>). Each component was measured as follows: a nearby weather station collected data on the amount of precipitation (P) by a tipping bucket gauge (Sierra Misco, Berkeley, CA) every 10 minutes. Total precipitation in 1986 amounted to 23.8 cm, which was less than the normal annual amount of 30 to 40 cm of precipitation (Dutt and McCreary, 1974). The amount of runoff (Q) from the plot was calculated by a modification of Evett's equation (Evett and Dutt, 1985), which relates precipitation to runoff for this type of catchment (Fig. 4). The coefficients used were, however, found by correlation of actual rain events and subsequent runoff from the plot under investigation (Arslan and Dutt, 1987, personal communication). The amount of irrigation (I) was measured by two Rockwell flow meters installed within the irrigation system. Two drip irrigations were supplied, one of 290 l on May 20 (day 75) and one of 382 l per plant on June 18 (day 104), totalling about 3.3 cm of water for each vine. The two irrigations were scheduled at average soil moisture tensions of -60 KPa at 25 cm and

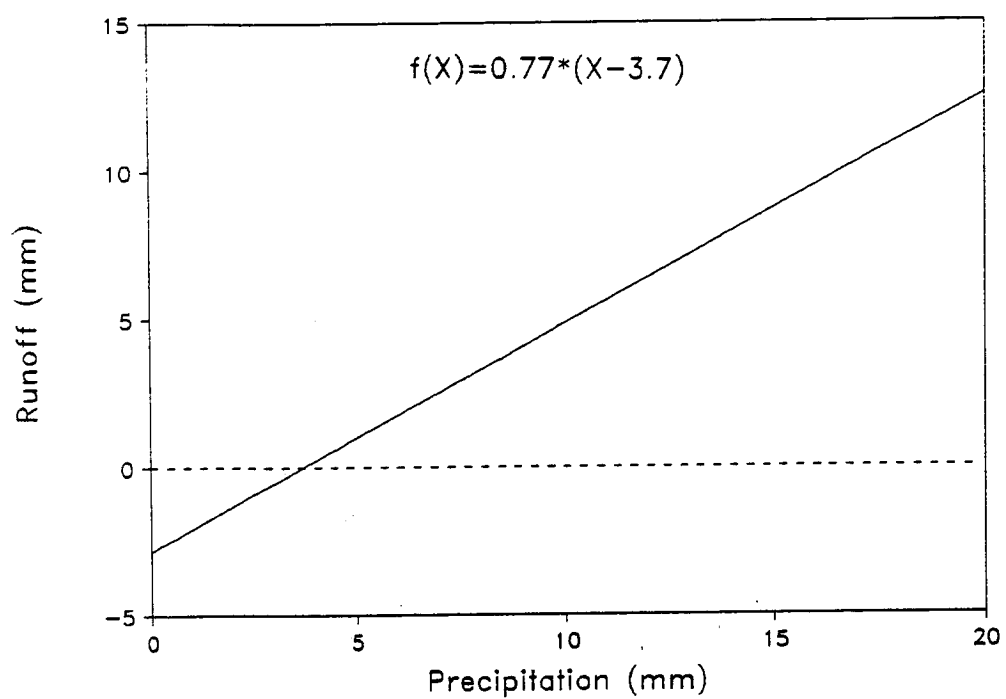


Fig. 4. Plot runoff (Q) and precipitation (P). -- Courtesy of A. Arslan and G. R. Dutt, 1987, personal communication.

-40 KPa at 50 cm, as measured by two tensiometers located 10 cm from each plant. The change in soil water storage ( $dS$ ) was calculated from the probe data with the aid of a microcomputer, as described below. For every date and site, the total depth of water measured around each tube was found to be negatively correlated to the distance from the tube to the plant. Integration of these functions yielded the total amount of water stored in the profile at that time. The difference between successive measurements at the same site gave the change in storage. By assumption, a positive change in  $dS$  indicated a soil water depletion, due primarily to ET. In the simplest case, when no precipitation, runoff or irrigation took place in the interval of time ( $dt$ ), then ET was equal to  $dS/dt$ . A negative  $dS$  indicated an increase in soil water storage and a corresponding subtraction of one or more of the components measured. Evapotranspiration was calculated from each site and interval of time to determine total seasonal ET.

In addition to the probe measurements, a Licor LI-1600 steady state porometer was used to monitor the plant stomatal response to irrigation. Porometer data were collected on the same plants used to determine soil moisture balance. Ten leaves per plant were chosen, representing both vegetative, fruit and non-vegetative sink leaves. Measurements were taken from April 15, 1986 to August 21, 1986

during the same days the probe readings were recorded. Daily measurements were taken every two hours from 8:00 a.m. to 4:00 p.m. (Mountain Standard Time) for each site.

The second part of this study employed healthy and vigorous cuttings of 'Cabernet Sauvignon'. The cuttings were collected from the University of Arizona Oracle Agricultural Center, were rooted in a greenhouse under intermittent mist and bottom heat for about six weeks. Upon the establishment of a vigorous root system, the vines were set into standard 4.4 l nursery cans and allowed to recover. The soil medium consisted of a uniform mix of two volumetric parts of peat, one of vermiculite and one of perlite. The soil was incorporated with recommended rates of Osmocote fertilizer to provide slow release nutrients (20:20:20).

Field capacity of the medium was determined, and a thermocouple psychrometer (Decagon SC-10) was used to determine the soil water content as a function of soil moisture tension ( $\psi_{\text{soil}}$ ). The plants were grown under standard greenhouse conditions. Once the plants achieved desirable size, four levels of water stress were imposed by a direct drying cycles lasting about 20 days. Three levels of  $\psi_{\text{soil}}$  (-0.4, -0.5, and -0.6 MPa) were reached by withholding water and monitoring the loss in weight. The control plants were kept above -0.2 MPa at all times.

Measurements of gas exchange were made with an open system with control over light, CO<sub>2</sub>, and vapor pressure. Two leaves per plant were chosen from the fourth and sixth node to be measured, and later the same leaves were detached to determine  $\psi_1$  using a PMS pressure bomb. A completely randomized design with 4 treatments and 48 replicates was employed. Concentrations of CO<sub>2</sub> at the mesophyll cell surface and CO<sub>2</sub> assimilation rates were calculated from standard equations (Moon and Flore, 1986).



## CHAPTER 4

### RESULTS AND DISCUSSION

#### Evapotranspiration

Neutron probe readings were taken at both sites as early as four weeks prior to bud break when plants were still dormant. These baseline readings indicated that a significant amount of water was stored within the profile and was well distributed in each layer. ET increased from  $9.8 \text{ ld}^{-1}$  from 8 days after bud break up to  $36.6 \text{ ld}^{-1}$  just before harvest (Table 2). ET declined rapidly after harvest, falling to only 34% of maximum ET by August 28, 1986 (Table 2). An initial rise in water consumption after bud break was related to vegetative growth (canopy development). Subsequently, a rise coincided with berry filling. ET declined after the berry filling stage during veraison and harvest (Table 2). Klein (1983) also observed a lack of a steady water consumption in grapes between filling and ripening (veraison) which may be related to their early maturing characteristic. Appreciable variation in ET rates between vines was observed before irrigation (Table 2). Plant A showed symptoms of water stress, as indicated by reduced vegetative growth and wilting earlier than plant B, due probably to differences in catchment length. This was

Table 2. Calculated Evapotranspiration (ET) in liters per day from bud break (day 0) to two weeks after harvest (day 168).

Date	Days From Bud Break	Growth Stage	ET (ld <sup>-1</sup> )			% of Max ET
			Plant		Mean $\pm$ SD	
			A	B		
March 7-14	8	Bud break	15.8	3.8	9.8 $\pm$ 6.0	27
March 21-28	22	Flowering	8.2	16.7	12.4 $\pm$ 4.2	34
April 4-11	36	Fruit Set	9.9	15.6	12.7 $\pm$ 2.8	35
May 7-20	75	Filling	21.7	24.4	23.0 $\pm$ 1.3	63
May 22-June 17	103	Filling	37.6	35.7	36.6 $\pm$ 0.9	100
June 19-July 23	139	Veraison	30.2	27.9	29.0 $\pm$ 1.1	79
August 15-21	168	Harvest	18.3	6.8	12.6 $\pm$ 5.7	34

\* Mean and Standard Error of the Mean between plant A and B respectively.

supported by lower ET rates and a reduced vegetative growth until day 36. Maximum ET was observed subsequent to the irrigations on day 75 and 103. Maximum ET rates were measured during the grape berry filling stage, which also coincided with the highest seasonal VPD (Fig. 5). Maximum percent of the total seasonal ET occurred between day 103 (second irrigation) and day 139. This period of maximum consumptive water use coincided with maximum water availability due to the second irrigation and to seasonal rainfall, which amounted to 5.4 cm. Lower vapor pressure deficits during this period were also correlated with higher values of stomatal conductance (Figs. 5 and 6). Thus, crop demand (berries containing about 20% of water (Smart and Coombe, 1983)), higher soil moisture availability and lower leaf to air vapor pressure deficits were concomitant with the maximum percentage of seasonal ET. Only 40% of total seasonal ET was observed between veraison and harvest (day 139-168), even though VPD values increased sharply, reaching their highest seasonal values (Table 2). Depletion of available soil water, reduction in crop water demand due to completion of berry filling, and decreased stomatal conductance with increasing VPD were factors reducing ET between veraison and harvest. At VPD values above 3 KPa, a sharp decline in  $g$  was observed, which led us to suggest that stomatal control is important in situations of low soil water availability and

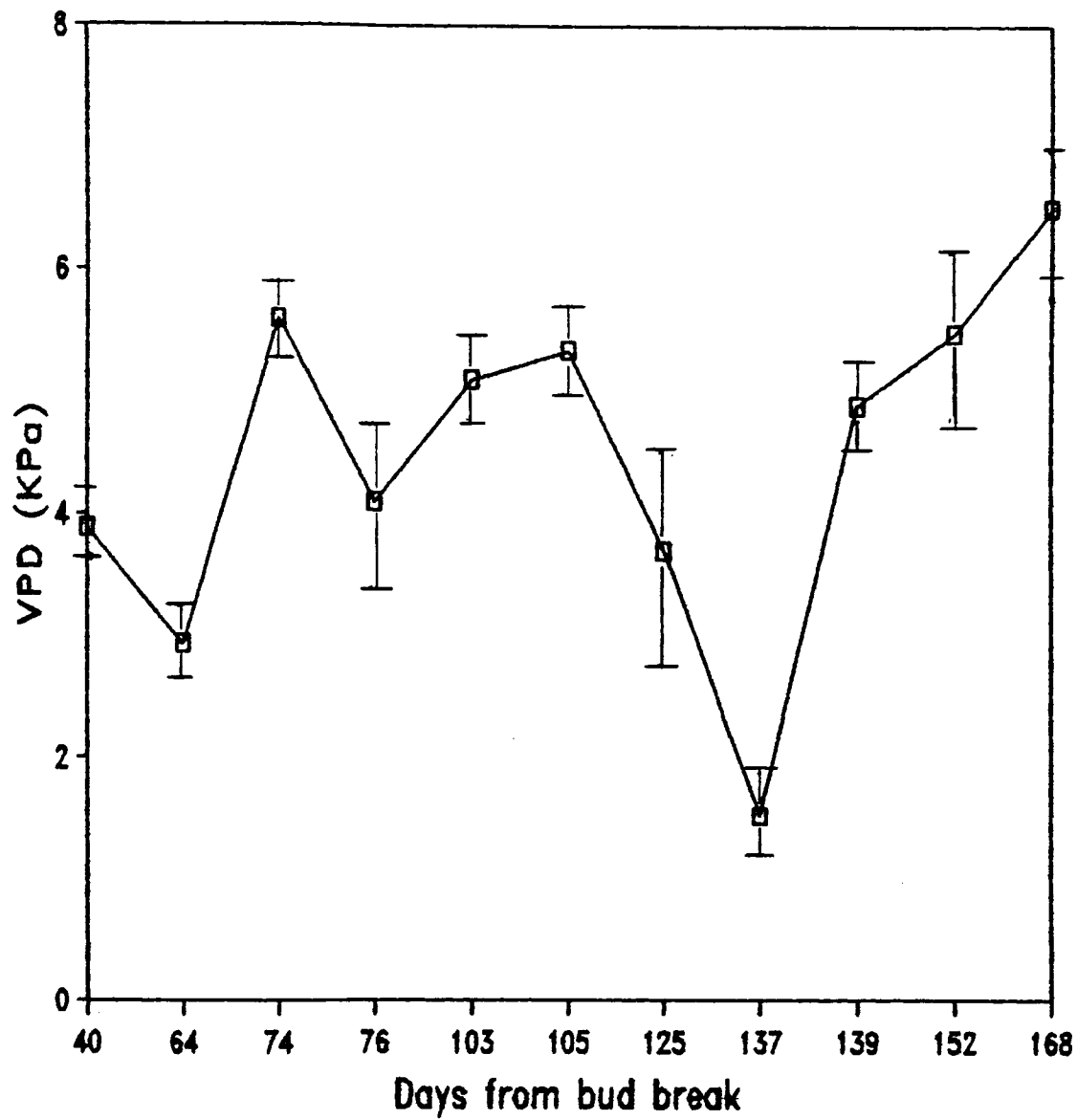


Fig. 5. Mean seasonal leaf vapor pressure deficit (VPD).-- Measurements taken from April 15, 1986 (day 40) to August 21, 1986 (day 168).

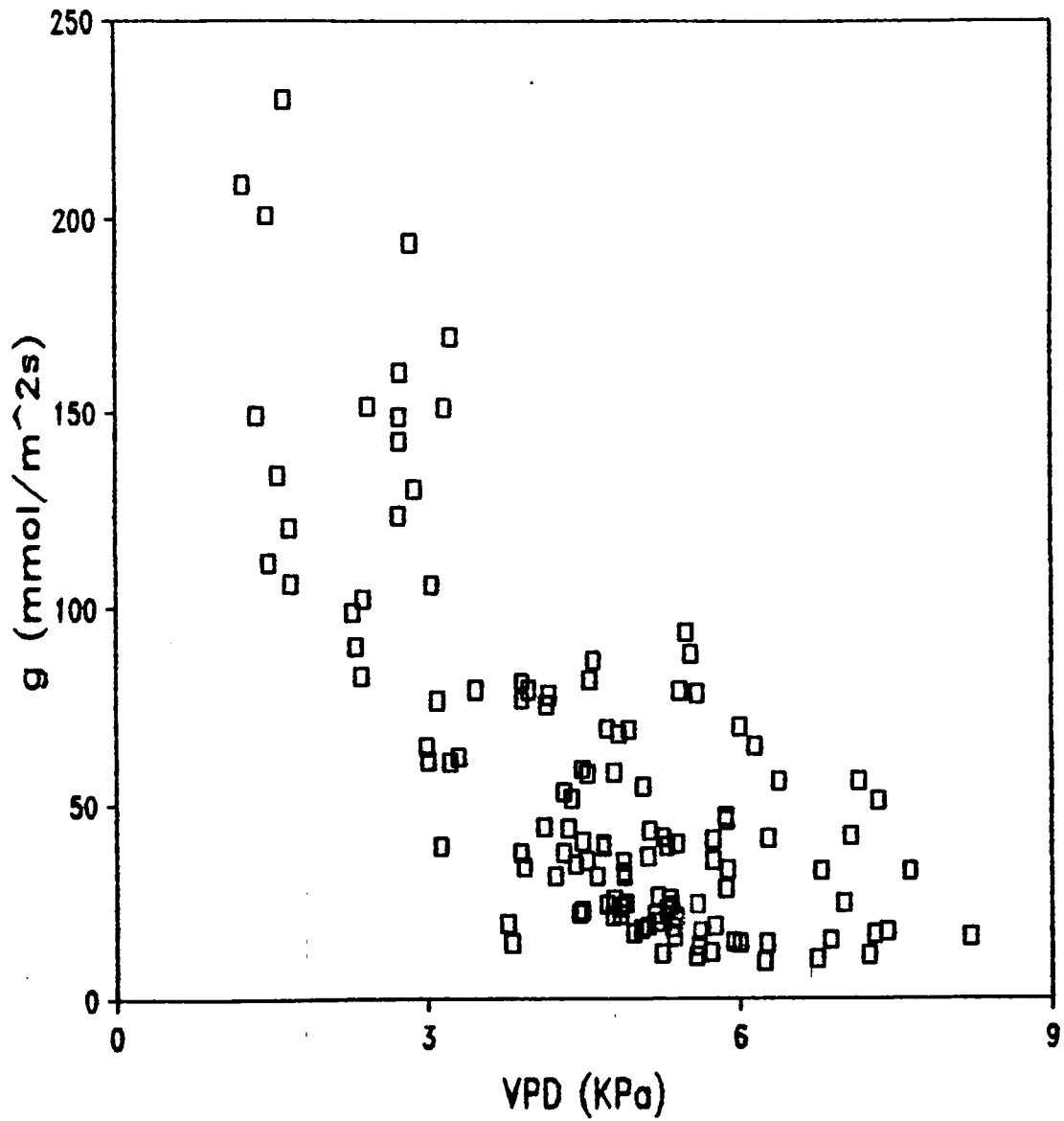


Fig. 6. Mean seasonal stomatal conductance ( $g$ ) and leaf vapor pressure deficit (VPD). -- Each square indicates the daily mean of ten leaves per plant from 4 plants.

intense evaporative demand. Seasonal response of stomatal conductance decreased logarithmically with increasing VPD (Fig. 6). The total seasonal ET for 'Cabernet Sauvignon' measured from bud break to two weeks after harvest amounted to 18 cm of water. It must be noted, however, that the row spacing in this experiment was almost double the size of commercial vineyards and that data were not collected throughout the season until leaf drop.

ET values reported for some wine varieties range from 18 to 60 cm (Table 3) when calculated for the whole growing season (bud break to leaf drop). In all cases, ET results were from direct measurements of soil moisture content and no information was provided about leaf vapor pressure deficit. The lowest ET values for 'Cabernet Sauvignon' were reported by Uttermohlen (1982) in a non irrigated vineyard in Northern California, a region where low pressure gradients can be expected. Values for 'Shiraz' grape reported from a warmer region in New South Wales, Australia, under presumably higher VPD, indicated a threshold level of both lowest (27 cm) and highest (60 cm) ET rates as determined by irrigation (Smart et al., 1974). The variability in ET between the two regions could be explained by differences in VPD, provided it had been measured.

Diurnal responses of  $g$  (Fig. 7) and TR (Fig. 8) were measured for both plants one day prior and one day after each

Table 3. Comparative values of total seasonal ET (cm) reported for four wine grape cultivars.

Location	Cultivar	ET (cm)
Alexander Valley CA <sup>x</sup>	'Cabernet Sauvignon'	18.5*
Carneros CA <sup>x</sup>	'Pinot Blanc'	25.1
Alexander Valley CA <sup>x</sup>	'Sauvignon Blanc'	26.2
San Joaquin Valley CA <sup>y</sup>	'St. Emillion'	29.9
Griffith, Australia <sup>z</sup>	'Shiraz'	27*-60
Present study	'Cabernet Sauvignon'	18.0

Symbols: <sup>x</sup> = Uttermohlen, 1982

<sup>y</sup> = Peacock et al., 1977

<sup>z</sup> = Smart et al., 1974

\* = Non irrigated

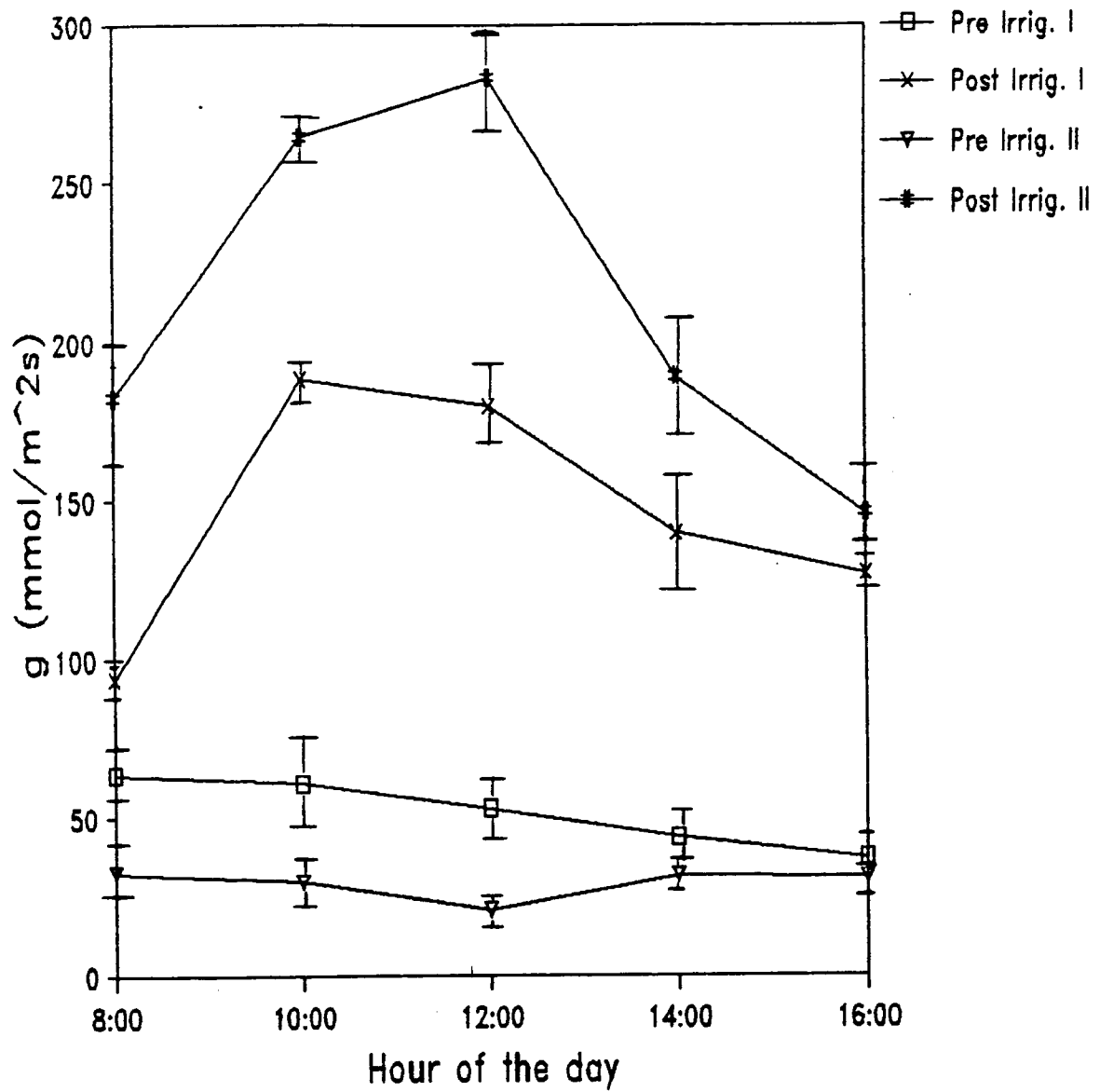


Fig. 7. Mean daily leaf stomatal conductance (g) measured before and after irrigations. -- Irrigation I: PPFD =  $1208 \pm 494$ ; and Irrigation II: PPFD =  $1177 \pm 437$  ( $\mu\text{mol s}^{-1}\text{m}^{-2}$ ).



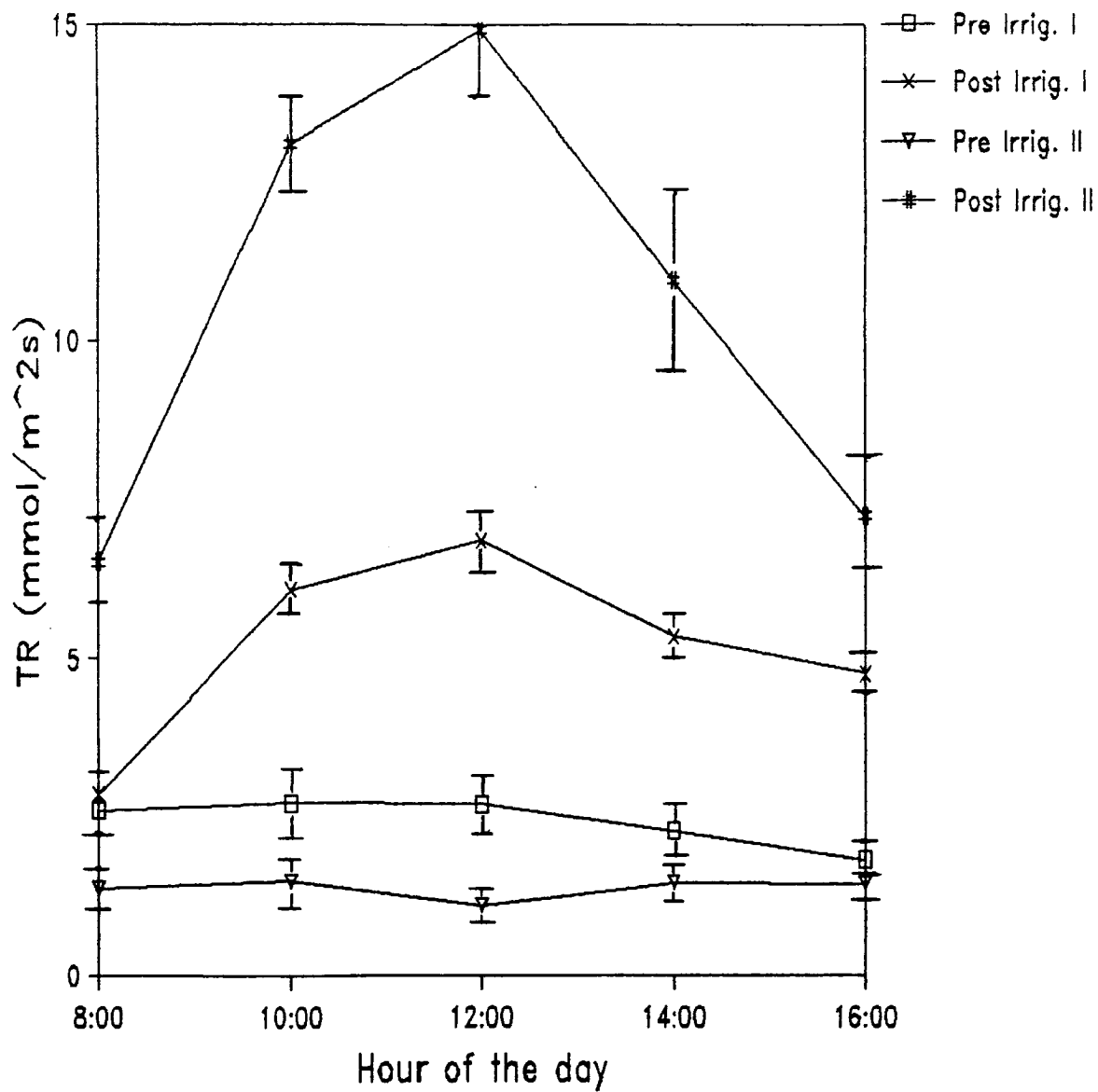


Fig. 8. Mean daily leaf transpiration rates (TR) measured before and after irrigations. -- PPFD data are reported in Fig. 7.

irrigation. On May 19, 1986 (Pre Irrigation I) and on June 17, 1986 (Pre Irrigation II), on both plants low  $g$  rates were observed throughout the day, due probably to water stress (minimum  $g = 25.49 \pm 11.85 \text{ mmolm}^{-2}\text{s}^{-1}$  on May 19). Indeed, after irrigations, diurnal  $g$  variations indicated a recovery from drought (maximum  $g = 273.66 \pm 36.14 \text{ mmolm}^{-2}\text{s}^{-1}$  on June 19). Highest  $g$  for well watered 'Cabernet Sauvignon' were reported to be  $114.6 \text{ mmolm}^{-2}\text{s}^{-1}$  (growth chamber), while maximum reported for field measured Vitis was  $192.7 \text{ mmolm}^{-2}\text{s}^{-1}$  (Korner et al., 1979). If water is available, grape stomatal conductance increases from dawn until midday and then it decreases again until dusk.

Several studies have reported stomatal closure in response to increasing VPD, even under non limiting soil water availability (Flore et al., 1985). However, when daily  $g$  rates continued steadily to decrease, even below night-time values, and VPD was high, the plants were experiencing water stress (Fig. 7). Transpiration rates, being directly related to  $g$ , showed the same response (Fig. 8). The second post irrigation maximum  $g$  values, being even higher than the first and higher than those reported by Korner (Korner et al., 1979), suggested that stomatal sensitivity to water stress and recovery increased progressively.

Since no measurement of total leaf area was taken, it seemed impractical to relate leaf transpiration rates

measured by the porometer to the whole plant or to the probe measurements. An effort was made, however, to compare these leaf transpiration rates with those reported by other investigators. The mean seasonal transpiration rate found for 'Cabernet Sauvignon' in this study measured  $57 \pm 47 \text{ mgm}^{-2}\text{s}^{-1}$ . The large variation observed could be explained mainly by differences between shaded and fully exposed leaves, and to high stomatal resistance during periods of water stress. TR measurements reported in other studies on grape vines range from 19 to  $57 \text{ mgm}^{-2}\text{s}^{-1}$  (Table 4). Rates reported by Smart and Coombe (1983) for 'Cabernet Sauvignon' seem low, even though they represent maximum values found under irrigation. However, the main difference from this study was that data were taken in a greenhouse under low evaporative demand. Field values obtained from 'Perlette' agree with the values found in this study.

The analysis of neutron probe data allowed at the same time the characterization of water extraction by each grapevine as a function of both the distance from the vine and depth. In this study, the change in soil water storage ( $dS$ ) due mainly to ET was found at three distances from the plant (0.4, 2.3, 4.7 m) for a soil depth of 2.5 m at 25 cm intervals (Fig. 9). The majority of soil moisture depletion (47.7%) attributable mainly to ET was found at 0.4 m distance from the vine (Table 5). No differences in soil moisture

Table 4. Reported values of transpiration rates (TR) for several grape cultivars.

Cultivar	Method/Place	TR ( $\text{mgm}^{-2}\text{s}^{-1}$ )	
		Maximum Irrigation	Water Stress
'Sultana' <sup>x</sup>	Gasometric/lab	44.4	2.8
'Perlette' <sup>y</sup>	Porometry/field	33.2	17.3
'Shiraz' <sup>z</sup>	Porometry/field	19.4	5.5
'Cab. Sauv.' <sup>k</sup>	Gravim./greenhouse	20.9	-
'Cab. Sauv.' <sup>l</sup>	Porometry/field	57.0	16.0

Symbols: <sup>x</sup> = Lovey's and Kriedemann, 1973

<sup>y</sup> = Safran et al., 1975

<sup>z</sup> = Smart, 1974

<sup>k</sup> = Smart and Coombe, 1983

<sup>l</sup> = Present study

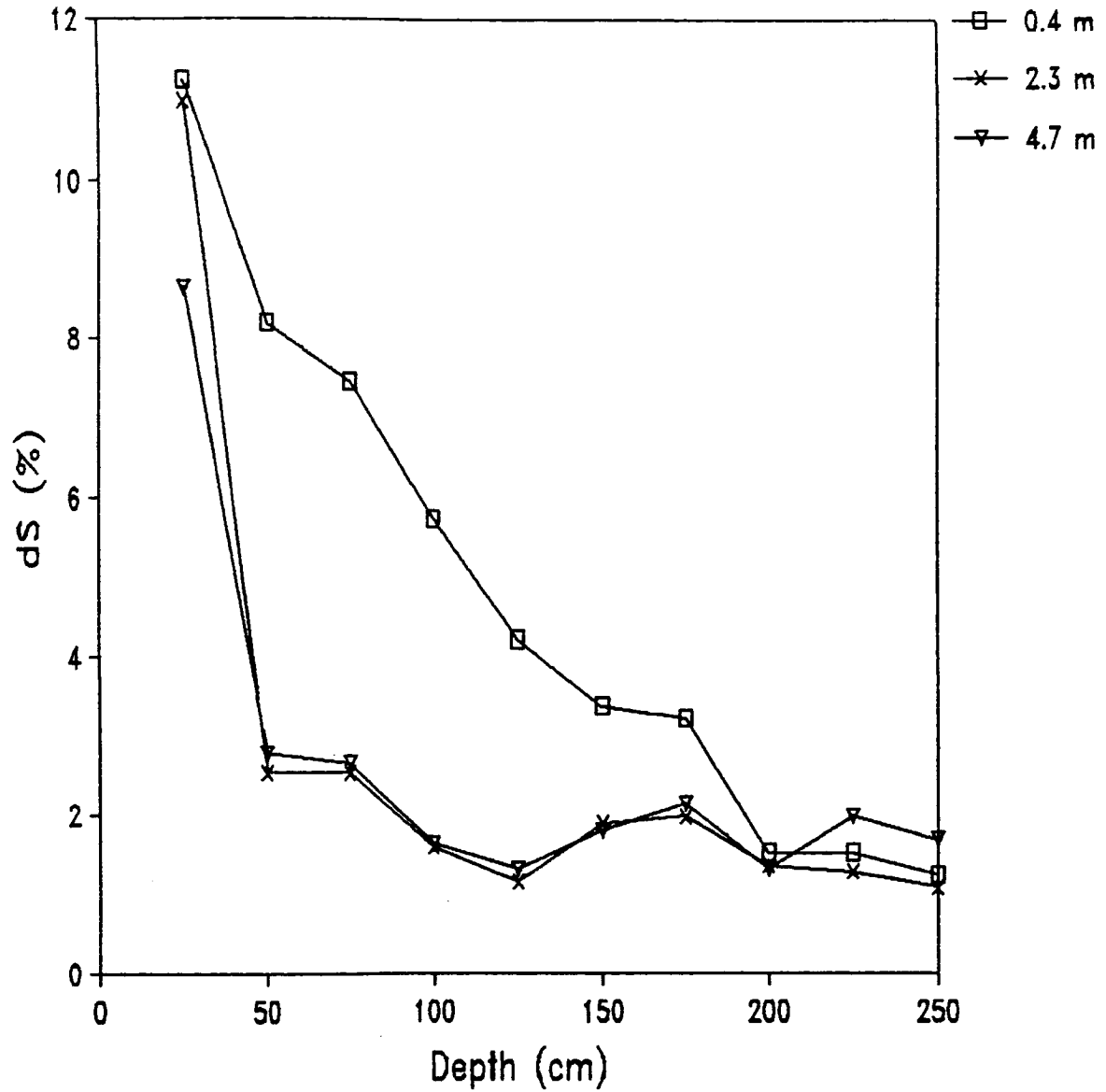


Fig. 9. Absolute change in soil water storage (dS) as a percentage of total change. -- 2.5 m deep soil profile, three distances (0.4, 2.3, 4.7 m) from the vine.

Table 5. Absolute change in soil water storage (dS) (2.5 m deep soil profile at 3 distances (0.4, 2.3, and 4.7 m) from the vine) as a percentage of the total seasonal dS.

Depth (cm)	dS (%)		
	Distance (m)		
	0.4	2.3	4.7
25	11.24	10.99	8.63
50	8.19	2.53	2.77
75	7.46	2.53	2.65
100	5.74	1.60	1.64
125	4.21	1.16	1.32
150	3.37	1.89	1.80
175	3.21	1.97	2.13
200	1.52	1.36	1.32
225	1.52	1.28	1.97
250	1.24	1.08	1.68
Sum	47.70	26.39	25.91

depletion were observed at 2.3 and 4.7 m spacings (Table 5 and Fig. 9). Van Zyl and Van Huyssteen (1980) suggested that the classical genetically determined pattern of root distribution, which expects most of water extraction in the upper part of the soil and very little in the deeper parts, may not be valid for grapevines. Data from this study indicated that 20 to 25% of water extracted was from root activity below 1.25 m. This suggested that grape roots form active root systems that will extract moisture from large soil volumes. Root activity below 1.25 m is further evidence that the vigorous 'Dogridge' rootstocks will exploit large soil volumes and will thereby be advantageous in moisture and nutrient uptake. Because of the extensive root distribution observed in these 'Dogridge' rootstocks, we chose an arbitrary rooting volume (previously shown in Fig. 1) as a basis for ET, representative of both crop and cultural characteristics.

Yield data collected for the two plants showed an average fresh berry weight of  $4.5 \pm 1.0$  kg per vine in 1986 as compared to the  $2.7 \pm 1.8$  kg average for the whole plot, whereas the same two plants yielded  $3.6 \pm 1.3$  kg in 1985 as compared to  $1.9 \pm 2.92$  kg for the whole plot. The increase in yield observed in plants A and B compared to both the previous year and to the rest of the plot in 1986 was attributable mainly to a change in irrigation management

employed. Although the total irrigation amount was the same in 1986 as in 1985, watering was scheduled in 1986 for plants A and B during two long applications only rather than frequent and low volume irrigations as was done in 1985. It should be pointed out, however, that in wine grape production yield cannot solely and adequately be expressed by weight, but it has to include other important enological parameters such as acidity, sugar content and total soluble solids, to mention a few. Thus, an ideal production strategy would be to schedule irrigation such as to achieve not the highest yields but rather optimal yield with excellent quality characteristics.

#### The Reduction in Carboxylation Efficiency

Mesophyll conductance progressively decreased as soil moisture tension and leaf water potential declined (Table 6). A marked depression was found in  $g'_m$  at soil potentials of -0.5 and -0.6 MPa. This caused a reduction in Maximum A (Max. A) of 42 and 70%. Evaluation of the slopes of the linear portion of the A versus  $[CO_2]_I$  response indicated that carboxylation efficiency was reduced (lower slope) as soil moisture potential became more negative (Fig. 10). Responses of 'Cabernet Sauvignon' grape to imposed soil moisture stress indicated progressive inhibition of photosynthetic capacity. The large reduction of mesophyll conductance observed in this study due mainly to soil moisture stress indicated that this



Table 6. The effect of soil water potential ( $\psi_{\text{soil}}$ ) on maximum  $\text{CO}_2$  assimilation (Max. A), leaf water potential ( $\psi_1$ ) and mesophyll conductance ( $g'_m$ ). -- Data were taken at light intensities of  $1620.7 \pm 531.9 \mu\text{mol s}^{-1}\text{m}^{-2}$  (PPFD), at temperatures of  $24.28 \pm 2.7 \text{ }^\circ\text{C}$ , VPD less than 2 KPa.

$\psi_s$ (MPa)	$\psi_1$ (MPa)	$g'_m$ ( $\text{mmol m}^{-2}\text{s}^{-1}$ )	Max. A ( $\mu\text{mol m}^{-2}\text{s}^{-1}$ )	Loss of Max. A (%)
-0.2	$-0.48 \pm 0.31$	21.1	$7.0 \pm 0.72$	-
-0.4	$-1.60 \pm 0.24$	17.4	$5.70 \pm 0.94$	18.0
-0.5	$-2.00 \pm 0.33$	9.0	$4.01 \pm 0.57$	42.4
-0.6	$-1.91 \pm 0.32$	4.2	$2.06 \pm 0.38$	70.4

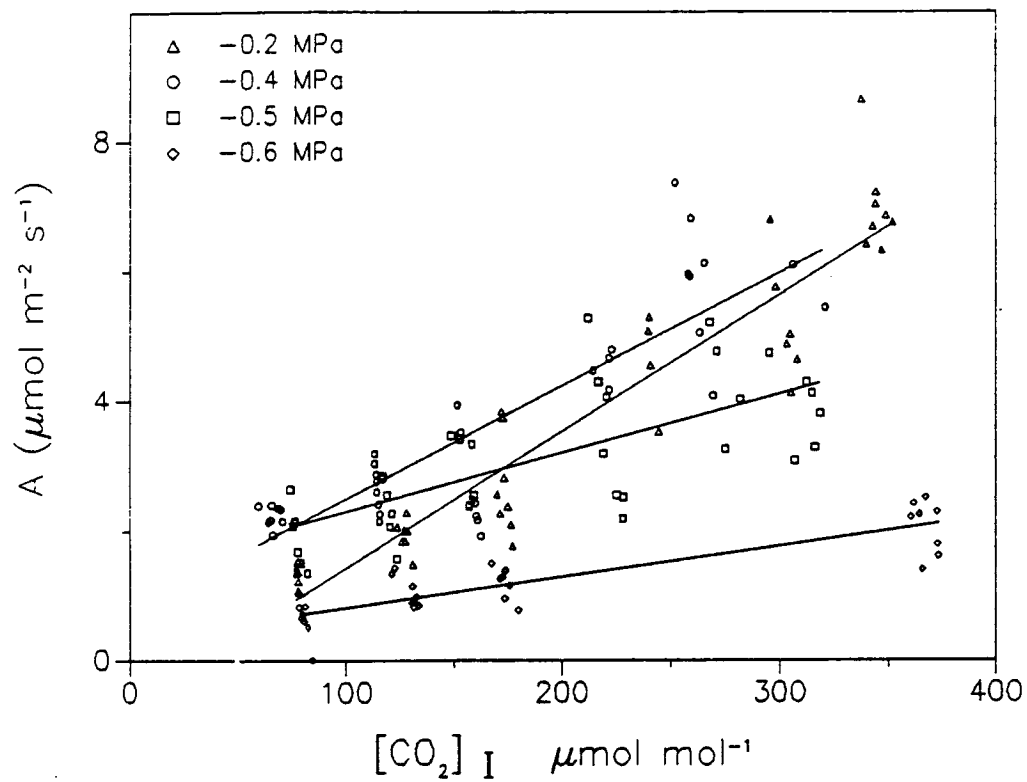


Fig. 10. Effect of increasing intercellular  $CO_2$  ( $[CO_2]_I$ ) on  $CO_2$  assimilation ( $A$ ). -- Environmental data are described in Table 6.

grape cultivar is not very drought tolerant. These results were in agreement with those found by Stoev and Slavcheva (1979) for the same grape cultivar (Table 7). Both Max. A and its relative loss reported in their study confirmed the severe damage (lower  $g'_m$ ) imposed to the photosynthetic capacity by increasing water stress. From the data presented in Table 7, it was noted that Max. A for 'Cabernet Sauvignon' are among the lowest reported for Vitis vinifera.

It should be pointed out that although the data summarized in Table 7 employed similar plant materials, significant differences in Max. A and  $g'_m$  can be found, depending on leaf age (Williams and Smith, 1985), and on the presence of fruit sinks (Giulivo et al., 1985). In conclusion, it seemed appropriate to compare the current findings for Vitis vinifera drought tolerance capabilities to those suggested by Lakso (1983) for apple trees. Three major mechanisms of drought resistance were suggested: "drought escape," "drought tolerance at high  $\psi_1$ ," and "drought tolerance at low  $\psi_1$ ." Drought escape applies to specific morphology and canopy architecture. Indeed, grape leaves, which are hypostomatous, are generally trained in tight canopies where a peculiar microclimate can be found; in addition, fruit are borne on short raceme, generally occupying the inner parts of the canopy, where considerably lower temperatures and VPD may be found. Drought tolerance at high

Table 7. Comparative effects of water stress on maximum CO<sub>2</sub> assimilation rate.

Cultivar	% of Field Capacity	Maximum A ( $\mu\text{mol m}^{-2}\text{s}^{-1}$ )	Loss of Max. A (%)
'Cabernet Sauv.' <sup>x</sup>	80	7.6	-
"	50	6.3	17
"	35	2.4	68
'Reichensteiner' <sup>y</sup>	70	-	-
"	30	-	67
'Riesling' <sup>z</sup>	-	9.1	-
'Concord' <sup>z</sup>	-	13.2	-

Symbols: <sup>x</sup> = Stoev and Slavcheva, 1979, Bulgaria

<sup>y</sup> = Reuther, 1983, West Germany

<sup>z</sup> = Lakso, 1982, U.S.A.

$\psi_1$  would imply a close coupling of  $g_1$  to  $[\text{CO}_2]_I$  and eventually lead to a better water use efficiency, as found true for apple. Lastly, drought tolerance at low  $\psi_1$  would be explained also in grapes by turgor maintenance through osmotic adjustment.

## CHAPTER 5

### SUMMARY AND CONCLUSION

The first objective of this study was to evaluate ET for 'Cabernet Sauvignon' grape planted in a low density runoff-catchment system in the semi-arid climate of Southern Arizona in a water harvesting system. Total seasonal ET rates (March 14, 1986 to August 28, 1986) measured 136.1 l per plant. Maximum ET rates were found from fruit set to berry filling ( $36.6 \text{ l d}^{-1}$ ). A high degree of stomatal control in situations of water stress was related to increased stomatal resistance. Under conditions of limited water availability, stomatal conductance was found to decrease sharply at increasing leaf to air vapor pressure deficits. Leaf transpiration rates varied widely during the season, from 16 to  $187 \text{ mgm}^{-2}\text{s}^{-1}$ , presumably due to their position within the canopy and due to water stress in the vine between periods of irrigation and precipitation.

More information is needed at present about leaf area index of determinate grape canopies as dictated by both pruning techniques and training. Evaluations should be made of vapor pressure deficits found within the microclimate of the canopy, especially when such wide row spacing is employed.

The second objective of this study was to evaluate the reduction in carboxylation efficiency of this cultivar under water stress. Indeed, maximum CO<sub>2</sub> assimilation, mesophyll conductance and leaf water potential decreased directly in response to decreasing soil moisture tension in 'Cabernet Sauvignon' grape. The limitations in CO<sub>2</sub> assimilation appeared to be due to non stomatal factors, as indicated by the reduction in mesophyll conductance. A depression of 70% in CO<sub>2</sub> assimilation rate was observed at -0.6 MPa compared to -0.2 MPa. The large reduction in mesophyll conductance observed in this study due to soil moisture stress indicated that the carboxylation efficiency of this grape cultivar is severely reduced under low soil moisture availability. Evaluation of the recovery of  $g'_m$  after a stress episode would better indicate whether irreversible damage has been done to the photosynthetic process.

Additional work is needed for the most commonly grown cultivars to evaluate cell elasticity and turgor maintenance at low water potentials. However, parallel studies are needed in the field to establish the delicate role linking atmospheric vapor pressure deficits to both stomata and, indirectly, to photosynthesis.

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