Canopy Temperature as a Water Stress Indicator in Vines[1)]

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Canopy temperature (CT) of vine plots subjected to drying cycles, and of well-watered control plots was measured with the aid of an infra-red thermometer in a full-bearing Colombar vineyard together with measurements of leaf water potential (LWP) and stomatal resistance (Rs). A decrease in transpiration rate due to water stress caused plant temperature to rise above that of the non-stressed control. A maximum temperature difference of 3,2°C was obtained. The infra-red thermometer proved itself accurate and facilitated rapid temperature determinations while measurements of CT integrated temperatures of individual leaves. Canopy temperature was significantly and linearly correlated with soil water content (SWC). The study indicated that the onset of vine water stress occurred at plant available water contents of 30% – 50%, coinciding with a CT increase of 1,16°C – 1,62°C above that of the control.

A reliable and easily obtainable measure to determine plant water stress should be the best approach for efficient irrigation scheduling in any crop. Methods currently in use are almost exclusively based on the measurement of soil water or computations of meteorological data, both giving only an indirect indication of the probable plant water stress.

When a plant lacks water its stomata close, principally due to a lack of turgidity in the guard cells. Transpiration and consequently the evaporative uptake of energy is hereby 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 obtaining representative measurements 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 by it. The introduction of the infra-red thermometer has, to date, indicated remote sensing to be a promising approach to the monitoring of water stress in a crop and ultimately as a guide for irrigation scheduling (Ehrler, 1973; Sandu & Horton, 1978; Idso, Jackson & Reginato, 1977; Gardner, 1979; Jung & Scott, 1980; Jackson, *et al.* 1981; Mottram, De Jager & Duckworth, 1983; Berliner, Oosterhuis & Green, 1984).

Advantages of the infra-red thermometer include the ability to give rapid and accurate surface temperature measurements without the problems of equilibration time and possible temperature changes associated with contact sensors (Berliner, Oosterhuis & Green, 1984). Furthermore, use of the infra-red thermometer makes it possible to extend temperature measurements from single leaves to whole canopies.

Several indices for the prediction of crop water status from measurements of CT have been proposed. One approach, first suggested by Aston & Van Bavel (1972), was used to relate large midday spatial variability in CT 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 CT 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 CT for a non-stressed plant on "gusty days" is higher than for a stressed plant on a quieter day.

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 (1983) to be a successful and practical stress index for maize under South African conditions.

Another approach developed by Fuchs & Tanner (1966) compared the measured CT to that of a reference, non-stressed plot. In this way the interference of confounding factors, such as changing atmospheric conditions, could be avoided and the differences in CT between plots could be related to the differences in LWP and Rs. The reference plot approach was used for 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 obtained when more complex approaches involving additional routine measurements were used.

The object of this study was to evaluate the use of the

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infra-red thermometer in vineyards by investigating the relationship between vine canopy temperature, soil water conditions and some plant physiological parameters relating to water stress.

MATERIALS AND METHODS

Experimental Plots:

The investigation was carried out in a full-bearing, trellised (factory system), *Vitis vinifera* cv. Colombar vineyard, which comprises a long-term irrigation trial at Robertson (Van Zyl, 1984). Consequently much data relating vine performance to various soil water regimes were readily available.

Experiment 1:

Initially two plots (T1 and T4) were selected to represent the two extremes of water availability. Within each plot, which comprised a test row between two buffer rows, five representative vines were selected, on which measurements were 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 of 1,0 m, the soil was allowed to dry out for the following four weeks, during which time, the various plant and soil parameters described below, were measured at approximately weekly intervals. Concurrent measurements were made on a control plot (T4) which was irrigated sufficiently to maintain a 90% soil water regime.

Experiment 2:

After completion of the first series of measurements the test plot (T1) was irrigated again at véraison and allowed to dry out for a seven week period. This drying cycle was followed by two irrigations of 50 mm each on 12/3/83 and 23/3/83 respectively, in order to determine plant recovery from water stress on the parameters of plant water status. Relevant measurements were taken at approximately weekly intervals until harvesting.

Experiment 3:

In order to effect a more rapid desiccation 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). Because the volume of soil wetted by trickle irrigation is restricted to that around the immediate area of the roots, it was assumed that once the tricklers were blocked, the time before appreciable water stress was experienced by the vines would be less than for a microjet irrigated soil. Five representative vines were selected from both the test and control areas. After five weeks, (a week before harvest), the test area was again irrigated. A further set of measurements was made the day before harvesting.

Measurements of Soil Water Status:

In experiment 1 tensiometers were installed at four depths viz., 200 mm, 400 mm, 600 mm and 800 mm at 350 mm distances from each of the five vines in the test plot (T1). The soil water potential was determined on the control plot (T4) by a single set of four tensiometers at the same distances and depths as in T1. In the trickler plot, (T10), four tensiometers were installed in the same manner as described above next to one of the five vines for each of the test and the control areas. Readings were normally taken daily at 08h00 until the measuring range of the tensiometers was exceeded.

The SWC was determined gravimetrically as well as with the aid of a neutron moisture meter on "plant measurement days". These determinations were carried out for each test vine and usually for at least two vines on control plots, at the same depths and at the same distances from vines as described for the tensiometers.

Measurement of Plant Water Status:

Leaf water potential was measured in a Scholander pressure chamber (Scholander *et al.*, 1965) pre-dawn and at 10h00, 12h00 and 14h00, the latter representing the hottest (most stressed) part of the day. These times were subsequently reduced to include only the pre-dawn and the 14h00 readings. One recently-matured sunlit leaf per vine (five per plot) was used for LWP. Stomatal resistance was measured with an automatic diffusion porometer immediately before the leaf was cut for the determination of LWP. 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.

Surface temperatures were initially measured on a sunlit leaf, a shaded leaf and the leaf canopy using a Telatemp Model AG-42 infra-red thermometer. Later, measurements on single leaves were discontinued. To measure the temperature of a sunlit or shaded leaf, the infra-red thermometer was held perpendicular to, and about 200 mm away from the leaf surface. This resulted in a target spot of 14 mm diameter. Three or more readings were taken per leaf. In addition, CT per vine was determined, initially by holding the instrument and later by clamping it to a stand, at a distance of 2 m from the canopy.

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 from that of the leaf canopy.

By means of a thermistor situated at the front of the infra-red thermometer the difference in temperature between the target surface and the prevailing ambient temperature can be measured. Throughout the early stages of the investigation it was found that the air temperature measured with an accurate mercury thermometer and that registered by the infra-red thermometer differed, confirming findings of other workers (Mottram, De Jager & Duckworth, 1983). This was thought to be due to heat and radiation exchange between the thermometer's outer casing and the thermistor.

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).

In experiment 1 an estimation of the difference in berry growth rate between the test plot (T1) and the control plot (T4) was made. The fresh mass of thirtytwo berries per vine, randomly selected from marked bunches, was determined 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 CT and the other plant physiological parameters.

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 ± 1,90
Canopy	= 30,85°C ± 1,09
Shaded leaves	= 30,19°C ± 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 slanting canopy was viewed horizontally from eye level. Measurements of CT from overhead, perpendicular to the plane of the canopy would have yielded values closer to that of sunlit leaves, as was confirmed during later tests.

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

The absolute values of the plant parameters of water stress, especially temperature, varied greatly throughout the investigational period obviously due to the prevalent atmospheric conditions (Fig. 1). Consequently elimination of the atmospheric effect on plant parameters of water stress was attempted by calculating differentials ($\triangle$) between test and control values. Differentials of SWC and LWP were taken as control values minus test values while $\triangle$Rs and $\triangle$CT were obtained through subtraction of control values from test values.

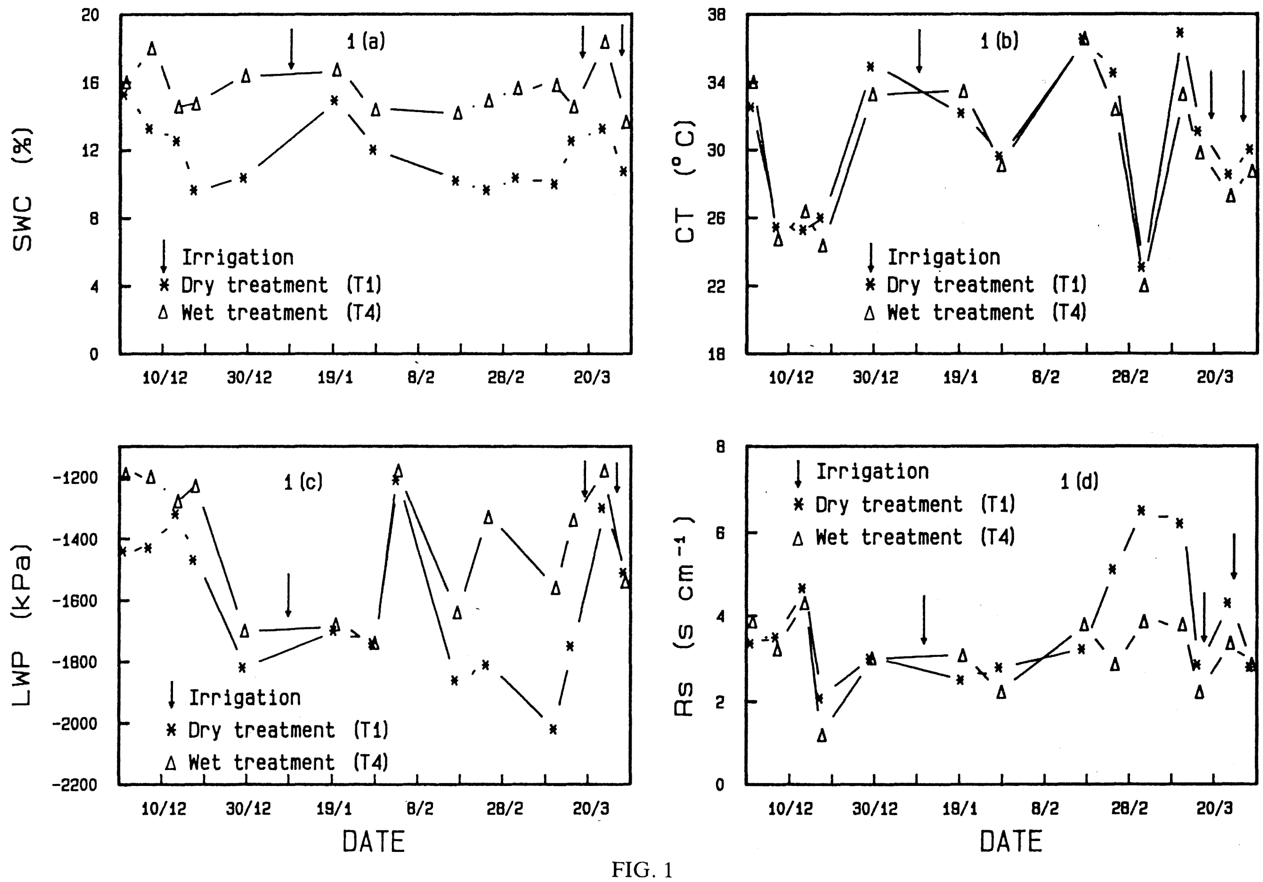

FIG. 1

Variation of soil water content (SWC) (mass %), canopy temperature (CT), leaf water potential (LWP) and stomatal resistance (Rs) in a Colombar vineyard on a dry treatment (T1) and a well-watered control plot (T4) at 14h00.

Experiment 1:

The difference in SWC ($\triangle$SWC) between T1 and T4, initially at the same SWC, increased during the course of the drying cycle. (Fig. 2a). Both LWP_p (LWP at predawn) differentials ($\triangle LWP_p$) (Fig. 2b) as well as CT differentials ($\triangle$CT) (Fig. 2c) correlated significantly with $\triangle$SWC (r = 0,85 and r = 0,98 respectively). Differentials of soil water content could in fact explain 97% of the variation in $\triangle$CT (Table 1). In contrast, $\triangle$LWP at 14h00 ($\triangle LWP_{14}$) (Fig. 2b) followed 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 conclusion of this experiment. Similarly, Rs differentials (△Rs) (Fig. 2d) 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.

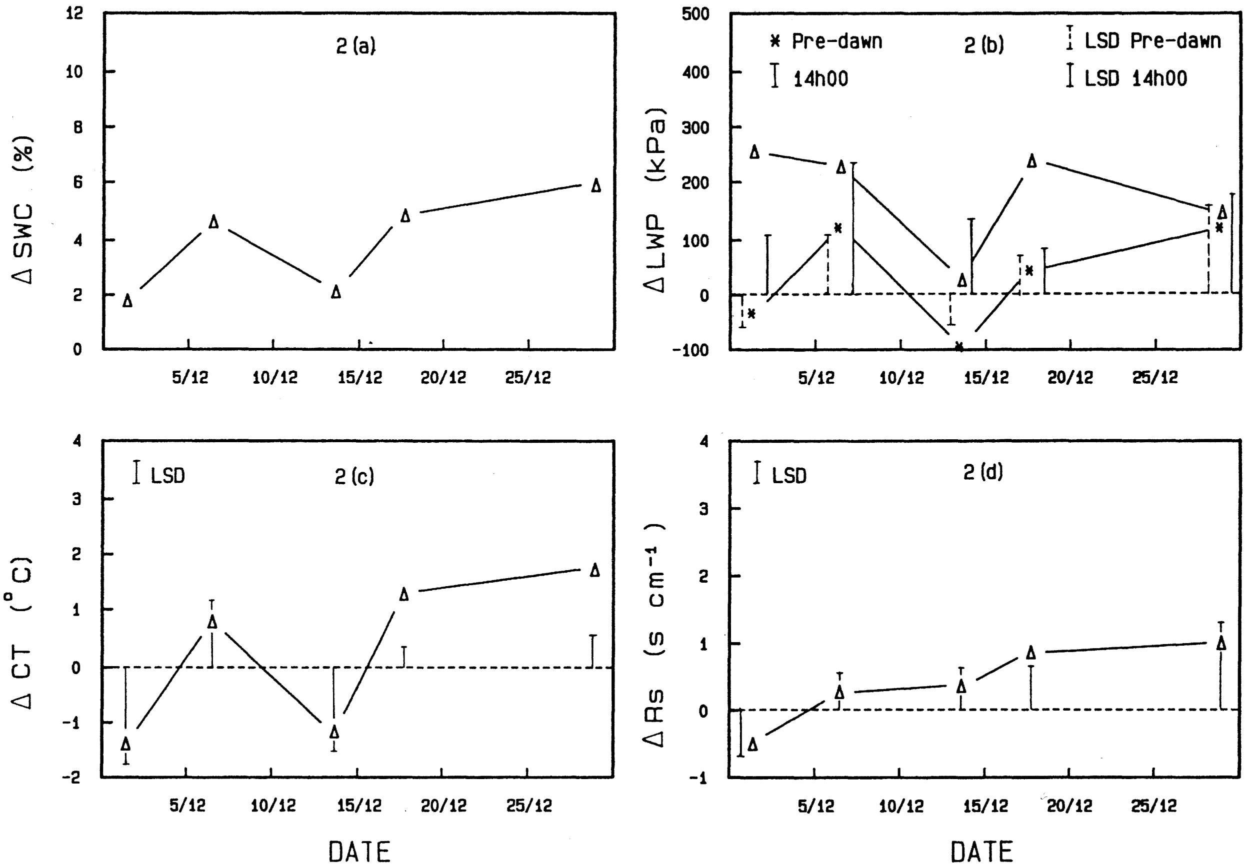

FIG. 2

Differentials (△) of soil water content (SWC) (mass %), leaf water potential (LWP), canopy temperature (CT) and stomatal resistance (Rs) determined in a Colombar vineyard in Experiment 1.

The onset of plant water stress was best indicated by △CT (Fig. 2c). 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 △LWP became significant on 29/12 for the first time, while 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. 3). Although the berry fresh mass of T4 was higher than that of T1 at the beginning of the experiment, the berry mass differentials remained constant until 13/12, indicating that the mass of berries from both control and test plots increased at similar rates. From then onwards i.e. on 17/12 and 29/12 the berry growth rate of T4 berries was much higher than that of T1 berries due to water stress in the latter.

Acceptance of 17/12/82 as the first date on which water stress was measured, coincided with a △SWC of 4,89% which, for this soil, corresponded to 36% plant available water (data not shown) i.e. that part of the water which can be held by the soil between field capacity and wilting point.

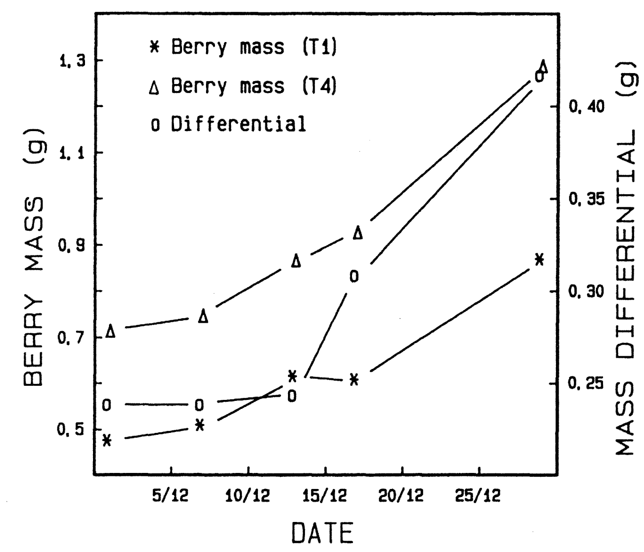

FIG. 3

Berry growth curves of Colombar on a well-watered control (T4) as well as on a dry test plot (T1) in Experiment 1.

Experiment 2:

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 △SWC in Fig. 4a. The plant parameters of water stress responded well to the changing soil water status. Pre-dawn values of △LWP (Fig. 4b) followed the variation in soil water status the closest (r = 0,82). Although $\triangle LWP_{14}$ was not significantly correlated with △SWC, this parameter clearly showed increasing vine water stress due to soil water depletion as well as the expected decrease caused by soil water replenishment.

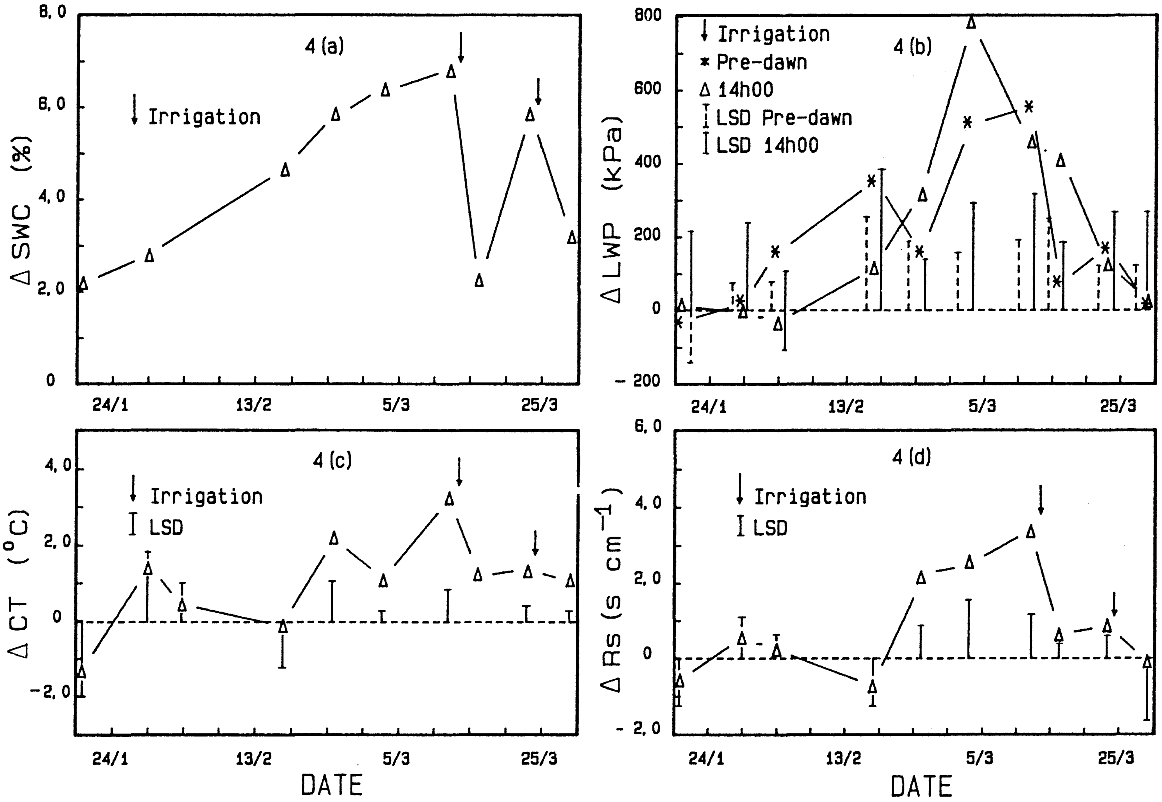

FIG. 4

Differentials (△) of soil water content (SWC) (mass %), leaf water potential (LWP), canopy temperature (CT) and stomatal resistance (Rs) determined in a Colombar vineyard in Experiment 2.

As in Experiment 1, canopy temperature differentials correlated significantly (r = 0,65) with △SWC (Table 1). Although △CT on 28/1 was unexpectedly large (statistically not significant) it should be ignored in determining the onset of water stress, in the light of values obtained on the following two measurement dates (Fig. 4c). 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 △Rs (r = 0,83) (Table 2).

TABLE 1

Statistical relationship between differentials (△) of canopy temperature at 14h00 and soil water content.

	Experiment 1 Dec. 1982	Experiment 2 Jan. 1983	Experiment 3 Tricklers	All Data
Regression Coefficient (r)	0,98★★	0,65★	0,73 NS	0,73★★
Coefficient of Determination (R^2)	0,97	0,42	0,53	0,53
Mean & Standard SWC (x)	3,66 ± 2,11	4,77 ± 2,37	6,21 ± 3,70	4,78 ± 2,61
Deviation 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 ($P \leqslant 0,05$)
★★ = Highly Significant ($P \leqslant 0,01$)
NS = Not Significant

TABLE 2

Statistical relationship between differentials (△) of canopy temperature and stomatal resistance 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	0,78★★
Coefficient of Determination (R^2)	0,25	0,69	0,02	0,61
Mean & Standard Deviation Rs (x)	0,24 ± 0,52	1,22 ± 1,27	2,42 ± 2,06	0,97 ± 1,19
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

Values of all plant parameter differentials declined considerably after the first irrigation (50 mm) 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 △CT were the exception in this case; they remained at 1,1°C above the zero line (Fig. 4c).

Onset of water stress was indicated by both △CT and △Rs to have occurred on 23/2/83 at a stage when △SWC was 5,14% corresponding to a soil water regime of 33%. However, plant water stress had already been indicated by significant values of △LWP at 14h00 on 16/2 (Fig. 4b) and on 2/2 by pre-dawn △LWP. Since some uncertainty exists regarding the effect of 25 mm 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 occurred at 46,3% plant available water which is considerably higher than that indicated by CT.

Experiment 3 (Tricklers):

At the start of this phase of the investigation, the soil water content of the test plots was already approaching permanent wilting point. This big difference in soil water content between control and test areas occurred throughout the experiment and was only eliminated by an irrigation on 23/2/83 (Fig. 5a). 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. 5).

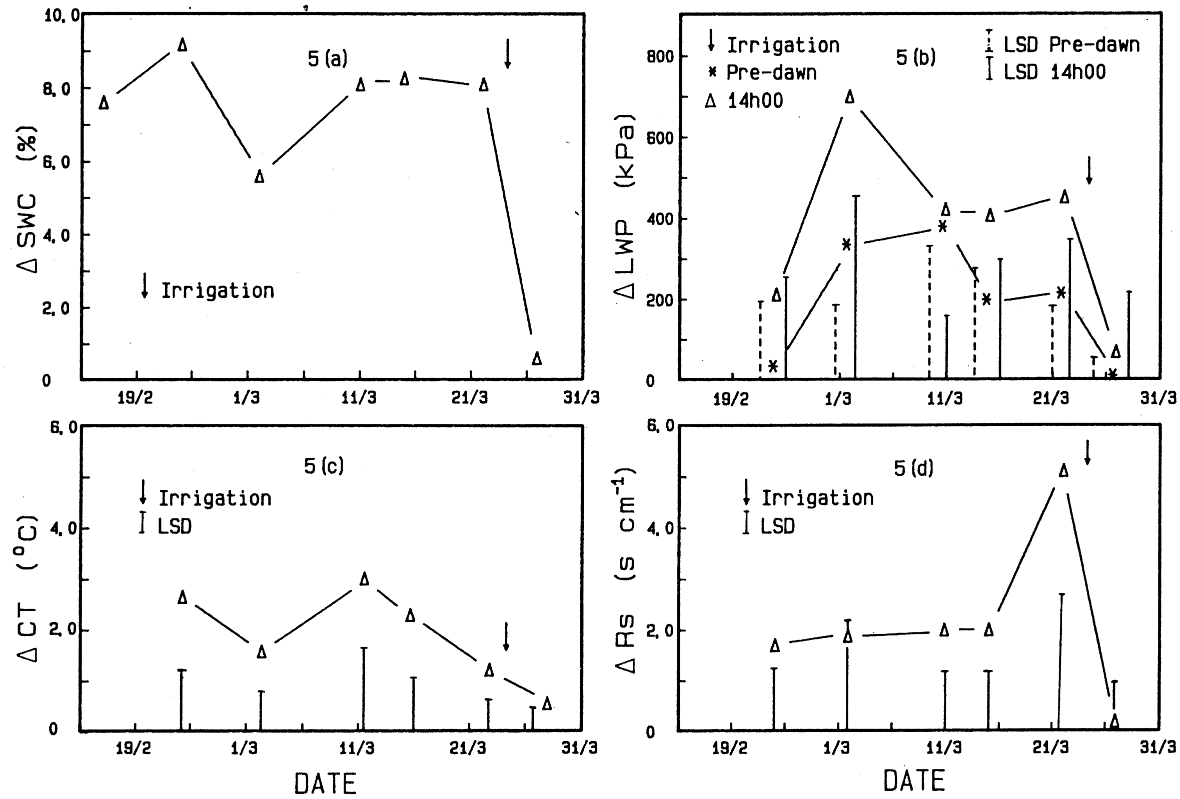

FIG. 5

Differentials (△) of soil water content (SWC) (mass %), leaf water potential (LWP), canopy temperature (CT) and stomatal resistance (Rs) determined on Colombar grapevines under trickle irrigation (Experiment 3).

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

Compiled data:

A statistical analysis of all data collected in the three experiments yielded a more reliable picture of the relationship between CT and 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. 6.

Despite non-significant regression coefficients between △CT and △Rs in Experiments 1 and 3, a significant correlation coefficient (r = 0,78) was obtained when the relevant data for all three experiments were analysed (Table 2, Fig. 7). However, △Rs could still explain only 61% 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

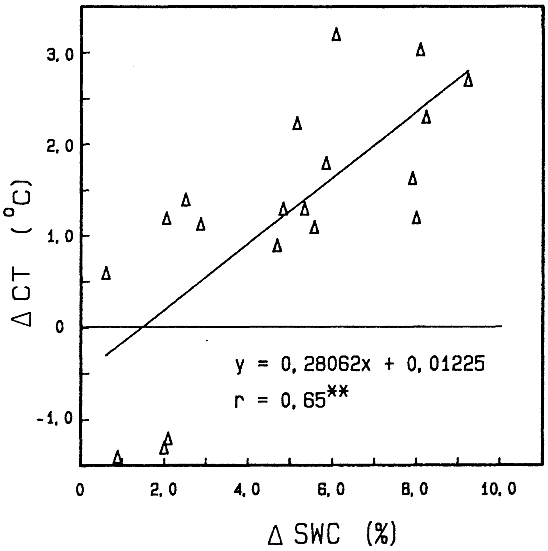

FIG. 6
Linear relationship between differentials (△) of canopy temperature (CT) and soil water content (SWC) (mass %) in a Colombar vineyard.

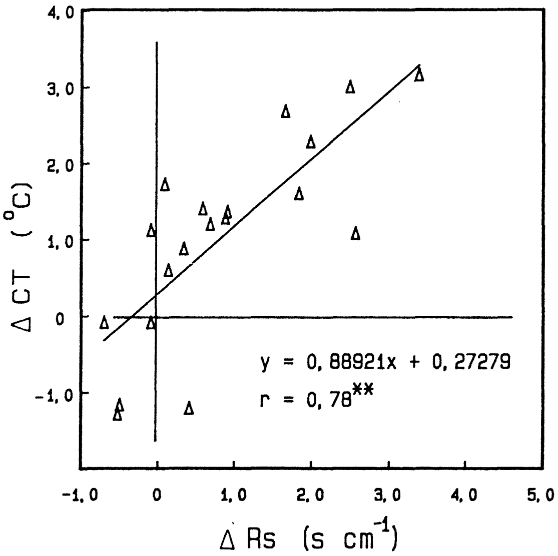

FIG. 7
Linear relationship between differentials (△) of canopy temperature (CT) and stomatal resistance (Rs) determined in a Colombar vineyard.

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.

TABLE 3
Statistical relationship between canopy temperature and leaf water potential determined at 14h00.

	Experiment 1 Dec. 1982	Experiment 2 Jan. 1983	Experiment 3 Tricklers	All Data
Regression Coefficient (r)	-0,56 NS	-0,64**	-0,81 NS	-0,68**
Coefficient of Determination (R^2)	0,32	0,41	0,65	0,47
Mean & Standard Deviation LWP (x)	-1 408 ± 213	-1 467 ± 246	-1 488 ± 227	-1 474 ± 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 ($P \leq 0,05$)
** = Highly Significant ($P \leq 0,01$)
NS = Not Significant

CONCLUSION

The infra-red thermometer proved itself to be reliable, easy to operate and an accurate instrument for the measurement of plant temperature. The configuration of the trellising system, as well as the complication of a bare soil background between rows, makes it more difficult to take representative temperature measurements of grapevine canopies.

Canopy temperature measured with the infra-red thermometer can be utilized successfully to indicate water stress in grapevines by comparing them to well-irrigated reference vines. The small temperature difference between irrigation and stressed plots in this present investigation – a maximum △CT = 3,2°C was measured – is a matter of concern. Despite these small differences in △CT however, the high accuracy of the infra-red thermometer and a low standard deviation of only 0,7°C (coefficient of variance = 2,4%) over the temperature range 30°C – 40°C, makes the measurement of canopy temperature potentially a viable tool for irrigation scheduling in vineyards.

In this study, CT, Rs and LWP_{14} were equally sensitive in their ability to indicate the onset of water stress. Pre-dawn LWP was a better indicator than these three parameters, but due to the ease and rapidity of temperature measurements with the infra-red thermometer, the application of the latter method in practical viticulture seems to have greater possibilities.

A critical △CT at which grapevines should be irrigated in order to prevent crop losses can be given provisionally. From the relationship between △CT and △SWC, it can be calculated that a 50% soil water regime, generally being used by farmers, corresponds to △CT = 1,16°C. If a critical range of soil water regimes between 30% and 50% is accepted, as suggested from this investigation, a corresponding △CT range of 1,16°C – 1,62°C is indicated. Consequently the possibility of applying CT as an indicator of vine water stress for the scheduling of high frequency irrigation, based on the principle of maintaining the soil water content close to field capacity, seems small.

These critical values of △CT proposed above should be tested and refined further before it can be applied in practice. Furthermore, the proposed critical values are not independent of the vapour pressure deficit and are consequently only valid for the Western Cape. Literature (Jackson, 1982) suggests that canopy temperature differentials will increase with a decrease in relative humidity.

The approach adopted in this investigation 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 eliminating the effects of fluctuating atmospheric conditions, and the fact that no additional metereological measurements as 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.

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