AN ABSTRACT OF THE THESIS OF

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Title: Using Infrared Canopy Temperature and Leaf Water Potential For Irrigation Scheduling in Peppermint (Mentha piperita L.)

Abstract approved:

Richard H. Cuenca

Several methods of inferring plant water stress for irrigation scheduling are based upon measurements of the environment in which the plants grow. These measurements include parameters such as soil water content, air temperature, pan evaporation and incident radiation. It is hypothesized that improved estimates of plant water deficit can be obtained by direct measurements made on the plants.

The main objective of this study was to test the performance of measurements of canopy temperature and leaf water potential for irrigation scheduling. This study seeks to establish whether a correlation exists between these monitoring methods and measurements of soil moisture content, leaf area, and evapotranspiration. The experiments were conducted in first-year peppermint irrigated at five
different rates. Canopy and air temperatures were measured with a hand-held infrared thermometer. Leaf water potential was measured with a pressure bomb.

A non-stressed baseline for the difference between canopy temperature and air temperature using data from well-watered plants was used together with the vapor pressure deficit to determine the crop water stress index (CWSI). The results of this study show that the CWSI is well correlated to evapotranspiration deficit and is useful for irrigation scheduling. The relationship between leaf area yield and CWSI in peppermint was described by a quadratic function.

Leaf water potential varied during the day in such a way that it was not possible to establish a relationship with water stress, differences in soil moisture content, or different irrigation levels. Leaf water potential was influenced by the daily weather conditions and represented the current demand more than the cumulative demand. The results of this study indicate that mid-day pressure bomb measurements cannot be used in irrigation scheduling. Predawn measurements of leaf water potential were stable, were well correlated with the different irrigation levels and soil moisture content, and therefore may be useful in irrigation scheduling.
Using Infrared Canopy Temperature and Leaf Water Potential for Irrigation Scheduling in Peppermint (*Mentha piperita* L.)

by

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Typed by         Ivan T. Gallardo
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# TABLE OF CONTENTS

1 INTRODUCTION ......................................................... 1

2 LITERATURE REVIEW .................................................. 4

   2.1 Crop Water Stress and Canopy Temperatures. .................. 4
   2.2 Measurements of Canopy Temperature .......................... 5
   2.3 Crop Water Stress Indices Based on Canopy Temperature ...... 6
   2.4 Use of the CWSI .................................................. 9
   2.5 Thermal Stress Index ............................................ 11
   2.6 Crop-Water Production Functions ............................... 12
   2.8 Leaf Water Potential Measurements With Pressure Bomb ..... 14
   2.9 Stress Effects on Leaf Water Potentials ...................... 19

3 MATERIALS AND METHODS ............................................. 22

   3.1 Site Characteristics .......................................... 22
   3.2 Experimental Field ............................................ 23
   3.3 Irrigation ..................................................... 24
   3.4 Temperature Data .............................................. 26
   3.5 Crop Status .................................................... 27
   3.6 Statistical Analysis ........................................... 28
List of Tables

Table 1. Average monthly temperature and precipitation...23

Table 2. Water applied for treatments.........................25

Table 3. Depth of water applied (cm).........................26

Table 4. Variation of $\Delta t$ during periods...............34

Table 5. Variation of $\Delta t$ during days.....................35

Table 6. Variation of $\Delta t$ during the day...............36

Table 7. Variation of $\Delta t$ for irrigation levels.........37

Table 8. Volumetric soil moisture content (%), one day after irrigation........................................38

Table 9. Volumetric soil moisture content (%), four days after irrigation........................................40

Table 10. Soil water depletion..................................41

Table 11. Leaf Area cm$^2$......................................44

Table 12. Values of stress degree day ° C....................47
List of Figures

Figure 1. Variation of diurnal canopy and air temperature the first day after irrigation ................. 30

Figure 2. Variation of diurnal canopy and air temperature the second day after irrigation ............... 31

Figure 3. Variation of diurnal canopy and air temperature the third day after irrigation ................. 32

Figure 4. Variation of diurnal canopy and air temperature the fourth day after irrigation ............... 33

Figure 5. Soil water profile distribution one day after irrigation. ........................................ 39

Figure 6. Soil water profile distribution the fourth day after irrigation. .................................... 40

Figure 7. Soil moisture content period variation one day after irrigation. .................................. 42

Figure 8. Soil moisture content period variation the fourth day after irrigation. .......................... 43
Figure 9. Variation of leaf area. ........................................ 44

Figure 10. Stress degree day. ........................................... 47

Figure 11. Theoretical upper and lower baselines. ............. 52

Figure 12. Nonstressed baseline. ....................................... 55

Figure 13. CWSI for different treatments. ......................... 56

Figure 14. CWSI for level T3, four different days. ............ 57

Figure 15. ET_d by water balance vs. CWSI. ....................... 58

Figure 16. LA deficit as function of CWSI. ......................... 61

Figure 17. Average plant stress distribution. ..................... 63

Figure 18. Distribution of plant stress during the day. ........ 64

Figure 19. Intersection between level T5 and level T2. ....... 65

Figure 20. Plant water tension curve. ................................ 66
USING INFRARED CANOPY TEMPERATURE AND LEAF WATER POTENTIAL FOR IRRIGATION SCHEDULING IN PEPPERMINT (*Mentha piperita* L.)

1 INTRODUCTION

Refined techniques are required for determining when crops need water so that water may be applied more efficiently. Several methods of measuring plant water stress, for monitor irrigation scheduling, are directly related to the plant status. Other irrigation scheduling methods monitor the environment surrounding the plants. Methods using environmental measurements, such as soil water content, air temperature, and solar radiation, are related to the plants requirements by some mathematical or statistical factor. All of these methods are time consuming to apply have restrictions on applicability, and contain significant sources of experimental error. The overall plant water status results from an integration of the atmospheric demand, soil water potential, root density and distribution, moderated by the genetic pattern and growth stage of the plant. Measurements should be made on the plant, rather than the soil or atmosphere, to obtain a true value of plant water deficit.
This study describes measurement plant water stress using two methods. The first approach employs an infrared thermometer to measure the infrared radiation emitted from peppermint. The second method employs a pressure bomb to measure the leaf water potential of the peppermint.

Crop canopy temperature is an indicator of the vegetal response to environmental factors that can stress the plants. Inadequate soil water stresses the plant, causing the plant to transpire at a rate less than the evaporative demand of the atmosphere. The water passing through the leaf surface through transpiration cools the leaves. As water becomes limiting, transpiration decreases and leaf temperature increases.

Leaf water potential measured with a pressure bomb is an indicator of plant stress level. The leaf water potential has been found to be quite responsive to changes in plant status (Scholander et al. 1965).

The main objective of this experiment was to test the performance of measurements of canopy temperature and leaf water potential for irrigation scheduling. This study seeks to establish the degree of correlation between the two monitoring methods and soil moisture content, leaf area, and evapotranspiration. The experiments were conducted in first-year peppermint irrigated at five different rates using a design described by Hancks (1976). Canopy and air temperatures and vapor pressure deficit were measured with
the SCHEDULER Plant Stress Monitor. Leaf water potential was measured with a pressure bomb PMS model 600.
2.1 Crop Water Stress and Canopy Temperatures.

Previous work comparing canopy and air temperature relations has been inconclusive. Miller and Saunders (1923), Eaton and Belden (1929) and Wallace and Clum (1938) reported peak leaf temperatures up to 7°C below air temperature. In comparison, Ehlers (1915), Curtis (1938), and Wagoner and Shaw (1952) found that leaf temperatures were higher than air temperatures. Ehrlcr (1973) measured leaf-air temperatures over different soil humidity contents and found differences from -3°C to +2°C and a reduction in leaf-air temperature difference of 1.3°C for each 1 kPa increase in vapor pressure deficit. Sandhu and Horton (1978) found leaf temperatures 2.5°C to 4.0°C higher for oats under water stress than well watered oats. Canopy temperatures have been proposed as a good indicator of plant water condition when compared to measured leaf water potentials, diffusion resistance, and relative turgidity (Idso et al., 1981B, 1981C, 1982A, and 1982B; O'Toole et al., 1984; Pinter and Reginato, 1982; Sharrat et al., 1983; Walker and Hatfield, 1983; Wiegand and Namken, 1966).
Canopy temperature is a satisfactory index of water stress because greater transpiration rates result in cooler leaf temperatures. In contrast, when evapotranspiration from the leaf is restricted, the absorbed radiation can warm the leaf above the air temperature instead of evaporating water (Baldocchi et al., 1983; Monchas et al., 1974; and Tanner, 1968).

2.2 Measurements of Canopy Temperature

Devices which measure emitted thermal radiation can be adjusted to read temperature. Monteith and Szeicz (1962) and Tanner (1963) were the first to use infrared (IR) radiometers for measurement of canopy temperature. Technological development has permitted a fast, non-contact method for measurement of surface temperatures. The radiation from the source is related to the surface temperature by the Stefan-Boltzmann law.

\[ R = \varepsilon \sigma T^4 \]  
(2.1)
where

\[ R = \text{radiation (W m}^{-2}) \]
\[ \varepsilon = \text{emissivity} \]
\[ \sigma = \text{Stefan-Boltzmann constant (5.674E-08 W m}^{-2} \text{K}^{-4}) \]
\[ T = \text{temperature (K)} \]

Most IR thermometers have a sensitivity in the range of 8 to 14 \( \mu \)m. Plant leaf emissivity varies in the range of .97 to .98 (Gates, 1964; Fuchs and Tanner 1966; Idso et al., 1969; Blad and Rosemberg, 1976).

2.3 Crop Water Stress Indices Based on Canopy Temperature

Canopy-air temperatures differences (\( \Delta t \)), were related to crop evapotranspiration (ET) and yield by several authors using the concept of stress degree days (SDD) (Lomas et al., 1972; Hiller et al., 1974; Idso et al. 1977, 1979, and 1980; Jackson et al. 1977; Walker and Hatfield 1979; Gardner et al., 1981B; Mtui et al. 1981; Hatfield 1983B; Bonanno and Mack, 1983). A relation between soil moisture deficit and positive SDD was showed by Jackson et al. (1977). By using \( \Delta t \) in corn of differentially watered plots, Heermann and Duke (1978) found that temperature rise above the well-
watered plots was negatively correlated with applied water and dry-matter yield. Temperature differences greater than 1.5° C were correlated with yield reductions. Gardner et al. (1981A) established that when the standard deviation of canopy temperatures in a plot was 0.3° C or greater, plants were water stressed. Clawson and Blad (1982) found that Δt of 0.7° between the test plot and well-watered plot indicated water stress.

Hand-held infrared thermometers have extended the measurement of plant canopy temperature from individual leaves to entire plant canopies. Canopy temperatures are dictated by the water status of the plants and by ambient meteorological conditions. The Crop Water Stress Index (CWSI) combines these factors to yield a measure of plant water stress (Jackson et al. 1988). Two forms of the index have been proposed, an empirical approach as reported by Idso et al. (1981) and a theoretical approach by Jackson (1981).

Idso's method requires the field measurement of Δt for a well-watered crop as a function of vapor pressure deficit (Idso et al., 1981A). This provides the lower baseline for a non-stressed crop. The upper limit for Δt, for an extremely stressed crop, depends on air temperature but is independent of the vapor pressure deficit (Jackson et al. 1988).
Reginato (1983) stated that the difference between the methods of Jackson and Idso is how to calculate the lower baseline. Jackson's method uses a fixed value for canopy resistance defined as the resistance to the diffusion of the water vapor between the intercellular spaces of leaves and the atmosphere at some height, while Idso's implies that canopy resistance varies through the day. But this difference should be small, since most measurements are taken one or two hours past solar noon and canopy resistance should be constant for most of the growing season.

Quantification of water stress by infrared thermometry is routinely carried out on complete plant canopies to minimize the influence of the soil surface. When plants are small or widely spaced, canopies may not be complete. Nielsen and Anderson (1989) working in sunflower (*Helianthus annus* L.) founded that calculations of CWSI from single-leaf temperatures measured with an infrared thermometer provided a rapid means of assessing plant water status in incomplete canopies.
2.4 Use of the CWSI

If a credible CWSI could be developed, the development of a direct and reliable irrigation management program would be possible. Also, the CWSI could provide a quick and easy technique for crop yield prediction (Idso et al., 1977; Geiser et al., 1982).

Jackson (1981, 1982) showed a relation between CWSI and the amount of extractable water used for wheat. The CWSI did not achieve a minimum until 5-6 days after irrigation, indicating a recuperative period. A single relation did not exist when the CWSI was plotted vs. water used due to this recovery period. This is partly due to the stage of crop growth and the corresponding amount of leaf senescence, as well as the changes in rooting volume, all necessary considerations when working with living experimental units. Hatfield (1983A), in comparison, found a close relation between the summation of CWSI and water consumed by the plants.

Hatfield (1983A) found that the sum of the CWSI of 1.5 would indicate 60% extraction of available water for sorghum. Geiser et al. (1982) used Δt for scheduling irrigation for corn. This resulted in a 39% reduction in water use compared to irrigation programming with resistance blocks, while yields were not significantly different.
Jackson (1982) suggested that the CWSI was theoretically related to the ET deficit (ET$_d$). ET deficit is defined as:

\[ ET_d = 1 - \frac{ET}{ET_p} \]  \hspace{1cm} (2.2)

where

\[ ET = \text{ET measured} \]
\[ ET_p = \text{ET potential} \]

The CWSI has been observed to follow a linear relation with the ET$_d$ measured by a hydrologic balance method (Idso et al., 1981B; Diaz et al., 1983). Although these regression analyses had high correlation coefficients, the presumed 1:1 ratio between seasonal ET$_d$ and CWSI was not observed. This highlights the relevance of local experimentation for a diversity of situations including planting dates and different types of plant architecture to calibrate the CWSI (Diaz et al., 1983).

A significant relation was found between the CWSI and photosynthesis (Idso, 1982; O'Toole et al. 1984). Research has shown it is possible to accurately forecast crops yields for wheat and corn using the CWSI (Diaz et al. 1983; Gadner et al., 1981). Reginato (1983) and Howell et al. (1984) found a negative linear relation between lint
yield of cotton and the average CWSI. Hattendorf et al. (1988) working in alfalfa (*Medicago sativa* L.) found yields were exponential functions of CWSI.

2.5 Thermal Stress Index

The Thermal Kinetic Window (TKW) was defined by Burke (1988) as a range of temperatures for optimal enzyme function. Mahan et al. (1987) established that the value of the apparent Michaelis constant (*Km*) define as the average velocity for of enzymatic reactions, had its minimum value and maximum insensitivity to temperature within the optimal thermal range of an organism. The thermal dependencies of the *Km* for glutathione and glyoxylate reductase were determined for spinach in the range of 12.5° to 22° C, for wheat between 17.5° and 23° C, for cotton 23° C to 32° C, and for cucumber 32° C to 42° C. These are considered to be the optimal thermal ranges for these species. Burke et al. (1988) showed a linear relationship between the time that foliage temperature were within their TKW and plant biomass production in wheat and cotton.
Thermal stress is difficult to separate from water stress. However linking enzyme kinetics to plant temperatures provides a new description of plant stress. Burke et al. (1990) developed the Thermal Stress Index (TSI) for cotton using the TKW as a biochemical baseline and found that the TSI and CWSI were highly correlated ($r^2 = .92$).

2.6 Crop-Water Production Functions

Crop-water production functions relate yield and water consumed by crops. Such functions are used for: (1) irrigation programming, (2) estimation of water requirements, (3) calculation of water use efficiency, (4) planning water use on a farm and regional levels, and (5) economic analyses (Cuenca et al., 1978; Stewart et al., 1975, 1977).

A gradient of water applied must be established to measure the crop yield reaction to different water supplies. Little and Hills (1978) and Hexem and Heady (1978) proposed an experimental design based in a complete randomized block. Hanks et al. (1976) proposed an alternative design called
the line source system using sprinklers. This method excludes randomization of the water applications and consequently does not allow for a valid estimate of the error for the irrigation main effect (Hanks et al., 1980). The benefits of the line source design include the reduction of experimental land area required and the fact that there is a continuous gradient of water application.

Vaux et al. (1981) reported a multiplicity of mathematical models for yield as a function of water applied. The quantification of drainage water through the root zone is important because it may contribute to the convex nature of the production function. The character of the yield vs. applied water crop production function implies that optimum water applications may be less than the water needed to guarantee that soil moisture content is not restricting ET (Ziska and Hall, 1983). It is not physically logical to presume ET and yield can increase linearly without limits. Theoretically, the yield versus ET production functions should have a segment of the curve where extra ET does not result in additional yield (Vaux et al., 1981). Downey (1972) proposed that the timing of ET deficits can influence yield to a greater degree than seasonal ET deficit. This suggests the complication of obtaining a single function of yield related to ET.
2.7 Leaf Water Potential Measurements With Pressure Bomb

Measurement of leaf water potential ($\Psi$) with a pressure bomb is usually regarded as a reliable and practical field technique (Meron et al., 1987). The pressure bomb is widely used in studies of plant water relations because of its relative ease of operation and versatility (Turner 1989). Improvement of the pressure bomb or pressure chamber by Scholander et. al (1964, 1965) simplified measurements of leaf-water potential under field conditions.

Using this procedure, a branch or leaf is cut and placed within a chamber that can be pressurized with a gas like nitrogen. The cut surface extends into the atmosphere through a seal in the top of the chamber. Pressure is slowly increased in the chamber until the meniscus in the leaf xylem just reaches the cut surface. This equilibrium pressure is an estimate of leaf-water potential (Boyer, 1967; Waring and Cleary, 1967; Tyree et al., 1974; Ritchie and Hinckley, 1975; Begg and Turner, 1976).

Two assumptions must be made in order to extrapolate pressure bomb readings to xylem potentials in the intact plant (Boyer, 1967). First, the leaf-water potential of the xylem sap and leaf cells must be in equilibrium during the time of measurement. Equilibrium occurs so fast that a
significant change in leaf-water potential cannot be detected after the initial balancing pressure is applied to the tissue. The second assumption is that water is ordered spatially in the same way in the shoot under pressure as it is in the plant. This assumption implies that the proportions of the conducting system during measurement represent those in the intact plant and the stem tissues are filled with water in the same way in both circumstances. In species without stem deformations and little pith, these assumptions are inaccurate (Boyer, 1967).

Care must be used when taking measurements to avoid water loss from the tissue after excision. The leaf-water potential of bare, fast transpiring, leaves was 2 to 7 bars lower than the leaf-water potential of leaves wrapped with a plastic sheath during the time from just previous to their excision to the completion of the measurements (Turner and Long, 1980). The error in the leaf-water potential of uncovered leaves arose from rapid water loss in the first 30 seconds after excision. The degree to which leaf-water potential decreased depended on the species, rate of transpiration, leaf-water potential at the time of excision, and whether the plants were grown in a greenhouse or outdoors (Turner and Long, 1980). Meron et al. (1987) found that the water potential of bare cotton leaves was about 2 kPa less than aluminum foil-wrapped leaves when the elapsed
time between excision to chamber pressurization was less than 30 s.

Wenkert et al. (1978) noticed that for bare leaves starting at -3 to -5 bars, leaf-water potential dropped as much as 1 bar during a single measurement due to dehydration associated with elevated tissue temperatures during compression. When the leaves were sheathed in more than one layer of plastic, they were effectively insulated from the temperature increase in the chamber and reductions in leaf-water potential were 0.1 to 0.2 bar per measurement. Purtich and Turner (1973) noted that although drying can start a soon as the tissue is excised, drying may be important within the chamber during measurement due to the large temperature increase from compression.

Significant spatial variation of leaf-water potential within herbaceous plants is theoretically predicted and supported by data (Ritchie and Hinckley, 1975). Care must be taken to obtain leaves which characterize the entire plant. Hoffman and Splinter (1968), working with tobacco (Nicotidiana tabacum L.), found that leaf-water potential became more negative in the lowest leaves of the canopy. Begg and Turner, (1970) found opposite results with more negative values higher in the canopy, and concluded that the gradient observed by Hoffman and Splinter (1968) resulted because the lower leaves were senescing and consequently gave erroneous conclusions.
The diurnal range of leaf-water potential has been found to be greater for leaves in the upper canopy than for those in the bottom (Clark and Hiler, 1973; Turner and Begg, 1973; Turner, 1974). Begg and Turner (1970) noted that at 1200 hr, $\Psi$ was 3 bars lower in the upper canopy of tobacco than at 1000 hr. In the bottom part of the canopy, $\Psi$ was only 1 bar lower at 1200 hr than at 1000 hr. Consequently the test procedures must involve either preparatory testing or normalization of the sampling method.

The most accurate technique of determining leaf-water potential is with a thermocouple psychrometer (Begg and Turner, 1976). This technique differs from the pressure bomb method (Scholander et al. 1964, 1965) and does not allow many measurements to be taken in a short time. Comparison of pressure bomb measurements with the thermocouple psychrometer indicated the agreement varies between species (Boyer, 1967; DeRoo, 1969; Hardegree, 1989). It is therefore essential to evaluate the pressure bomb for every species. Working with soybeans, Boyer and Ghorashy (1971) compared these two methods and found a correlation coefficient of 0.957 when $\Psi$ ranged from -3 to -25 bars.

Only the gravitational and the frictional component due to head pressure lost by friction of leaf-water potential in the xylem or transpiration stream are measured by the pressure bomb, not the osmotic and the matrix components due
for water retention by the plant tissue. The combined gravitational and frictional components are referred to as P, the xylem pressure potential (Ritchie and Hinckley, 1975). Calibrations with the thermocouple psychrometer are desirable when the pressure bomb is employed to evaluate leaf-water potential. When P values are used only as relative index of water status, calibration may not be necessary as P itself is a meaningful indicator of plant water stress.

Dickey (1982) reported that predawn plant-water tension is function of soil moisture content while daytime plant-water tension is climatically controlled. He found that the predawn plant-water tension approached the soil-water tension during the night, but depended on type of plant and the capability to measure xylem pressure and osmotic pressure. For some plant species, the pressure bomb method can yield accurate data in a short time and is a practical tool for estimating leaf-water potential and, thus, plant water stress levels on a relative basis.
2.9 Stress Effects on Leaf Water Potentials

It has been shown by many researchers that leaf-water potential measured with a pressure bomb is a consistent indicator of plant stress level, (Begg and Turner, 1970; Clark and Hiler, 1973; Day et al., 1981; Meyer and Ritchie, 1980; Rawson et al., 1978; Turner et al., 1978). Working with southern peas, Clark and Hiler (1973) demonstrated that, readings of \( \Psi \) from stressed plants were 4 to 0.7 bars lower than non-stressed plants at predawn and midday, respectively during the vegetative stage of growth. During pod development, the leaf-water potential readings of stressed plants were about 1 bar lower than non-stressed plants throughout the day.

Working in irrigated sorghum (\textit{Sorghum bicolor} L.) and sunflower, Turner et al. (1978) noted that the mean daily minimum leaf-water potential did not decrease below -17 and -20 bars, respectively, but did decrease to -21 in non-irrigated sorghum and to -26 bars in non-irrigated sunflower. Working in spring barley (\textit{Hordeum vulgare} L.) Day et al. (1981) determined the effects of drought on leaf-water potential. Irrigation ranged from none to well watered. During the day, leaf-water potential decreased to a minimum of -15 to -18 bars for irrigated plants and was 3 bars lower for those non-irrigated.
Gardner and Niemann (1964) showed that leaf-water potential is dependent on diurnal environmental variations under conditions of high soil-water potentials. At low soil-water potentials, leaf-water potential was closely related to the soil-water potential (Gardner and Niemann, 1964; Sivakumar and Shaw, 1978; Rudich et al., 1981). Contrary to these arguments, Dickey (1982) demonstrated that plant-water tension measured during the day was climatically controlled for any soil-water potential and predawn plant-water tension was controlled only by soil moisture content.

The diurnal change of leaf-water potential is an effect on the excess of transpiration over absorption. Leaf-water potential can be used to appraise the plant's reaction to atmospheric conditions over a period of several hours (Elfving et al., 1972). The diurnal fluctuation of leaf-water potential occurs due to two conditions. When, soil moisture becomes limiting and resistance to water flux in the soil increases, the diurnal curve tends to plateau around midday and even to show a momentary recovery. However, if soil moisture content is high, leaf-water potential, measured diurnally in the field, usually reproduces the atmospheric evaporative demand curve (Ritchie and Hinckley, 1975).

Many researchers have reported diurnal fluctuations in leaf-water potential (Jordan, 1970; Clark and Hiler, 1973; Turner, 1974; Sivakumar and Virmoni, 1979; Day et al.,
Working with spring barley, Day et al. (1981) noted a 12 bar decrease in leaf-water potential from predawn to midday with non-irrigated treatments usually being 3 bars lower than irrigated treatments. Sivakumar and Virmoni (1979), working in chickpea (Cicer arietinum L.), noticed that when the soil was dry, leaf-water potential remained very negative past midday and as late as 1700 h, indicating that the plants were under severe stress. However, when soil moisture was satisfactory, only one negative peak was reached at midday, after which the plants quickly recovered. For arid zone species, diurnal curves tend to begin at low leaf-water potential values and gradually decrease throughout the day, only recuperating a little at night (Ritchie and Hinckley, 1975).
3 MATERIALS AND METHODS

3.1 Site Characteristics

In summer 1991, a study was performed on plots in a 60 m by 150 m field at Central Oregon Agricultural Research Center in Madras. The soil was classified as a Madras loam with less than 1% slope. The soil was moderately deep and medium-textured with an indurated calcareous hardpan at 75 cm. Permeability was moderate. The available water holding capacity of these soils ranged from 0.12 to 0.25 cm of water per cm of soil. Effective potential rooting depth was 50 to 75 cm. Runoff was slow to medium and the hazard of erosion is slight to moderate with sprinkler irrigation. The site elevation is 900 m above sea level. The average annual precipitation is 228 mm, average air temperature is 7.7° C to 10° C., and the frost free season is 50 to 80 days at 0° C and 100 to 130 days at -2.2° C (USDA, 1970).

Table 1 shows the average monthly air temperatures for the site.
Table 1. Average monthly temperature and precipitation.

<table>
<thead>
<tr>
<th>Month</th>
<th>Temperature (°C)</th>
<th>Precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>-0.83</td>
<td>29.4</td>
</tr>
<tr>
<td>Feb</td>
<td>1.72</td>
<td>19.3</td>
</tr>
<tr>
<td>Mar</td>
<td>4.50</td>
<td>15.7</td>
</tr>
<tr>
<td>Apr</td>
<td>7.67</td>
<td>13.9</td>
</tr>
<tr>
<td>May</td>
<td>11.27</td>
<td>25.6</td>
</tr>
<tr>
<td>Jun</td>
<td>15.00</td>
<td>20.0</td>
</tr>
<tr>
<td>Jul</td>
<td>18.77</td>
<td>6.3</td>
</tr>
<tr>
<td>Aug</td>
<td>17.83</td>
<td>6.3</td>
</tr>
<tr>
<td>Sep</td>
<td>13.89</td>
<td>15.5</td>
</tr>
<tr>
<td>Oct</td>
<td>8.61</td>
<td>16.0</td>
</tr>
<tr>
<td>Nov</td>
<td>3.39</td>
<td>30.7</td>
</tr>
<tr>
<td>Dec</td>
<td>0.22</td>
<td>29.2</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>228.3</td>
</tr>
</tbody>
</table>

3.2 Experimental Field

Each experimental unit consisted of a strip 5 m wide and 15 m long with four replications. Peppermint rows were parallel to a line source sprinkler line (Hanks et al., 1976), replicated four times, selected at random from the entire plot. The rate of irrigation decreased linearly from the sprinkler line outward. The rows were oriented east-west with 70 cm spacing.
The field was planted with peppermint (*Mentha piperita* L.). The peppermint plant is shallow rooted and cultivated like as perennial crop that is vegetatively propagated from rootstock or stolons. Roots and shoots grow from nodes on the stolons. Peppermint requires large amounts of water during the growing season, but it does not tolerate water-logged soils (Lacy et al., 1989).

### 3.3 Irrigation

The amount of irrigation applied in each plot ranged from 110% to 45% of the water requirement of peppermint (Watts et al. 1968), with a irrigation interval of 5 days. Table 2 shows the water projected to apply as a percentage of the mint water requirement.
Table 2. Water projected to apply for treatments.

<table>
<thead>
<tr>
<th>Irrigation Level</th>
<th>T5</th>
<th>T4</th>
<th>T3</th>
<th>T2</th>
<th>T1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Applied %</td>
<td>110</td>
<td>90</td>
<td>70</td>
<td>55</td>
<td>45</td>
</tr>
</tbody>
</table>

Different proportions of the water requirements were applied as a function of the distance from the line source. Water was applied on August 10, 15, 20, 24 and 29, 1991. Catchment containers were placed in each irrigation level. After irrigation, the water inside the containers was measured and converted to depth of irrigation as shown in Table 3.
Table 3. Depth of water applied (cm).

<table>
<thead>
<tr>
<th>Date</th>
<th>T5</th>
<th>T4</th>
<th>T3</th>
<th>T2</th>
<th>T1</th>
</tr>
</thead>
<tbody>
<tr>
<td>August 10</td>
<td>2.20</td>
<td>1.65</td>
<td>1.32</td>
<td>1.06</td>
<td>0.84</td>
</tr>
<tr>
<td>August 15</td>
<td>1.60</td>
<td>1.42</td>
<td>1.20</td>
<td>0.91</td>
<td>0.55</td>
</tr>
<tr>
<td>August 20</td>
<td>1.65</td>
<td>1.36</td>
<td>1.05</td>
<td>0.83</td>
<td>0.66</td>
</tr>
<tr>
<td>August 24</td>
<td>2.41</td>
<td>1.99</td>
<td>1.57</td>
<td>1.22</td>
<td>0.96</td>
</tr>
<tr>
<td>August 29</td>
<td>1.65</td>
<td>1.22</td>
<td>0.60</td>
<td>0.55</td>
<td>0.50</td>
</tr>
<tr>
<td>Average</td>
<td>1.90</td>
<td>1.53</td>
<td>1.15</td>
<td>0.91</td>
<td>0.70</td>
</tr>
<tr>
<td>Actual % of requirement</td>
<td>113</td>
<td>91</td>
<td>69</td>
<td>55</td>
<td>42</td>
</tr>
</tbody>
</table>

3.4 Temperature Data

Foliage temperature, air temperature, and relative humidity were determined by a portable infrared thermometer (SCHEDULER Plant Stress-Monitor). The instrument had a field of view of 5 degrees, a sensing window of 8 to 14 μm, and a resolution 0.2° C. Sampling range was from 2.54 cm to 300 m. The air temperature was measured from aspirated air with an accuracy of 0.1° C. The relative humidity was measured from aspirated air with an accuracy of ± 5%. The accuracy for the instrument was tested and verified by the Oregon State University Hydrological Science Laboratory in Gilmore Hall.

Foliage temperature was measured with the infrared thermometer facing a predominantly northern direction. The
thermometer was held about 30 cm above the canopy at about a 45 degree angle from horizontal. Air temperature and humidity were measured at the same time as foliage temperature. Wind speed was measured 30 cm above the canopy by a Casella London Model I524 anemometer. Canopy temperature, air temperature, and vapor pressure deficit, were measured daily in each irrigation zone between 700 and 1500 PST beginning four months after planting and continuing until harvest.

The data were collected during four growth periods of four days each at six times during the day; 700, 900, 1200, 1300, 1400, and 1500 PST.

3.5 Crop Status

Gravimetric measurements of volumetric soil moisture content were made one day and four days after irrigation at depths of 0-5, 5-10, 10-15, 15-20, 20-30 and, 30-45 cm.

Plots of 2400 cm² were used for measured leaf area, four times, directly from the field without destroying the plants.
Water tension was measured in plant leaves at 500, 600, 800, 1000, 1200, 1400, 1600, 1800 and, 1900 PST. One randomly selected leaf fully expanded near the top of the plant canopy was excised at the base of the petiole and placed in a pressure chamber (PMS Instrument Co., Corvallis, OR., Model 600) within 10 seconds for determination of water tension.

3.6 Statistical Analysis

Analysis was according to Hanks et al. (1980) for a line source sprinkler. The effects of the irrigation level are statistically nonvalid due to lack of randomization. However, the analysis of variance does provide valid error terms for testing the effects of other variables and their interactions with irrigation levels if the treatments are randomized, using linear regression analysis and or analysis of variance. The analyses were done using the software package SAS.
4 RESULTS AND DISCUSSION

4.1 Diurnal Changes in Canopy Temperature

Canopy temperature reached a daily maximum value earlier than did air temperature (Figs. 1, 2, 3, 4). Canopy temperatures were always lower than air temperature before dawn. During the first day after irrigation, at noon, the less-watered treatments level T1 and level T2 had canopy temperature values greater than air temperature (Fig. 1). By the second day after irrigation, all the treatments had canopy temperatures greater than air temperature, but only treatments levels T1, T2, and T3 maintained higher canopy temperature in the afternoon (Fig. 2). During the third day after irrigation, all the treatments developed higher canopy temperature from mid-morning to mid afternoon, but only levels T1, T2, and T3 maintained a higher canopy temperature until 1500 PST (Fig. 3). During the fourth day after irrigation, all the treatments had a higher canopy temperature from mid-morning until 15 PST (Fig. 4). These data are in agreement with the results of Ehler et al. (1978) and Palmer (1967).
Figure 1. Variation of diurnal canopy and air temperature the first day after irrigation
Figure 2. Variation of diurnal canopy and air temperature the second day after irrigation.
Figure 3. Variation of diurnal canopy and air temperature the third day after irrigation
Figure 4. Variation of diurnal canopy and air temperature the fourth day after irrigation
4.2 Variation of Canopy-Air Temperature Difference

The difference between canopy and air temperature ($\Delta t$) was influenced by soil, plant, and climatic factors.

\[ \Delta t = \sum_{d=0}^{n} \sum_{h=0}^{m} \sum_{r=0}^{l} \frac{\Delta t_{nml}}{nml} \]  \hspace{1cm} (4.1)

where

d = days

h = hours

r = repetitions

The effect of crop growth on $\Delta t$ was noticeable during the season. Table 4 shows the mean variation of $\Delta t$ for different periods over all treatments. No significant differences were found between treatments (5% level)

<table>
<thead>
<tr>
<th>Period</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta t$ °C</td>
<td>1.49</td>
<td>0.87</td>
<td>0.93</td>
<td>0.38</td>
</tr>
</tbody>
</table>

The temperature of the crop is a function of how much energy is received from the sun or advective heat and how
much is dissipated by heat exchange with the air. With increasing leaf area, there is a subsequent decrease of bare soil percentage changing the albedo that influences the crop and surrounding air temperature.

The daytime value of Δt was correlated to soil water content. The gradient of Δt was from -0.98 °C for day 1 to 2.57 °C for day 4. The soil water content decreased with time after irrigation and this change was coincident with changes in Δt (Table 5).

Table 5. Variation of Δt during days.*

<table>
<thead>
<tr>
<th>Day After Irrigation</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δt</td>
<td>-0.98a</td>
<td>0.69ab</td>
<td>1.41ab</td>
<td>2.57b</td>
</tr>
</tbody>
</table>

*Mean followed by the same letter are not significantly different by Fisher protected LSD range test, 5% level.

The time of day when the data were collected influenced Δt.
where
p = periods
h = hours
r = repetitions

At 700 and 1500 PST, At was negative, but at 1300 At was at its maximum for all treatments (Table 6). This variation in At during the day was related to changes in the atmospheric demand, principally solar radiation, which affected soil, air, canopy temperatures and the vapor pressure deficit. At at 700 was influenced by the effect of dew on the leaves. Shortly after sunrise, the dew evaporated decreasing the leaf temperature. At at this hour is therefore related as much to atmospheric condition as plant response.

### Table 6. Variation of Δt during the day

<table>
<thead>
<tr>
<th>Time</th>
<th>700</th>
<th>900</th>
<th>1100</th>
<th>1200</th>
<th>1300</th>
<th>1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δt</td>
<td>-1.22a</td>
<td>1.04ab</td>
<td>1.49ab</td>
<td>1.86b</td>
<td>2.41c</td>
<td>-.05ab</td>
</tr>
</tbody>
</table>

*Mean followed by the same letter are not significantly different by Fisher protected LSD range test, 5% level.

The irrigation level effect on Δt is shown in Table 7. Level T5 with 110% of the peppermint water requirement, develops a small value of Δt. Level T1 with 45% of the peppermint requirement, had Δt value of 1.68.
Table 7. Variation of Δt for irrigation levels averaged over all times

<table>
<thead>
<tr>
<th>Irrigation level</th>
<th>T5</th>
<th>T4</th>
<th>T3</th>
<th>T2</th>
<th>T1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δt</td>
<td>0.06</td>
<td>0.58</td>
<td>1.01</td>
<td>1.27</td>
<td>1.68</td>
</tr>
</tbody>
</table>

It is apparent from Table 7 that the radiometric temperature of a vegetation canopy depended on soil moisture. Drying of the root zone gradually from field capacity to some relatively small fraction of field capacity gradually lead to an increase in leaf temperature.

4.3 Soil Water Content

Soil water content (SWC %) one day after irrigation are shown in Table 8. The treatments that received more water from irrigation had the higher soil water content levels. Levels T5 and T4 have nearly saturated upper soil layers allowing for water movement to the deeper layers, and increasing soil water content in these layers (Figs. 5 and 6).
Table 8. Volumetric soil moisture content (%) one day after irrigation.

<table>
<thead>
<tr>
<th>Soil Depth (cm)</th>
<th>Irrigation Treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T5</td>
</tr>
<tr>
<td>0 - 5</td>
<td>29</td>
</tr>
<tr>
<td>5 - 10</td>
<td>30</td>
</tr>
<tr>
<td>10 - 15</td>
<td>31</td>
</tr>
<tr>
<td>15 - 20</td>
<td>33</td>
</tr>
<tr>
<td>20 - 30</td>
<td>34</td>
</tr>
<tr>
<td>30 - 45</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 9 shows soil water content values four days after irrigation. The depletion of soil water content was principally in the first 20 cm for the well-watered treatments and in the first 30 cm for the less-watered treatments T1 and T2 (Figs. 5 and 6). The zone in which the plants take the water from the soil is related to their root depth. In this experiment, the root depth was observed principally in the first 30 cm of the soil with 80% in the first 20 cm. This explains the observed water depletion from this shallow zone.
Figure 5. Soil water profile distribution one day after irrigation.

The variation of accumulated soil water content from irrigation to irrigation is shown in Figures 7 and 8. The soil water content for level T5 was stable with a tendency to increase. In treatments T4 to T1 soil water content showed a tendency to decrease with time.
Figure 6. Soil water profile distribution the fourth day after irrigation.

Table 9. Volumetric soil moisture content (%) four days after irrigation.

<table>
<thead>
<tr>
<th>Soil Depth cm</th>
<th>Irrigation Treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T5</td>
</tr>
<tr>
<td>0 - 5</td>
<td>28</td>
</tr>
<tr>
<td>5 - 10</td>
<td>28</td>
</tr>
<tr>
<td>10 - 15</td>
<td>28</td>
</tr>
<tr>
<td>15 - 20</td>
<td>28</td>
</tr>
<tr>
<td>20 - 30</td>
<td>29</td>
</tr>
<tr>
<td>30 - 45</td>
<td>33</td>
</tr>
<tr>
<td>Average</td>
<td>29.9</td>
</tr>
</tbody>
</table>
Table 10 shows the average soil water depletion (cm) for each irrigation level. The values indicated are the average differences between soil-water content one day after irrigation and four days after irrigation cumulative over the profile from four periods.

Table 10. Soil water depletion (cm) for the five irrigation treatments

<table>
<thead>
<tr>
<th>Irrigation Treatments</th>
<th>T5</th>
<th>T4</th>
<th>T3</th>
<th>T2</th>
<th>T1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.35</td>
<td>1.25</td>
<td>1.1</td>
<td>0.95</td>
<td>0.75</td>
</tr>
</tbody>
</table>
Figure 7. Soil moisture content period variation one day after irrigation.
4.4 Leaf Area

The variation of leaf area (LA) over time is shown in Table 11 and Figure 9. The LA is the best representation of yield in peppermint, the final product of peppermint crop is oil coming from the leaves, for lack of accuracy in the technique of oil extraction in small samples, in this research the yield is represented by LA.
Figure 9. Variation of leaf area.

Table 11. Leaf Area cm² for the five irrigation treatments

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Period</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P1</td>
<td>P2</td>
<td>P3</td>
<td>P4</td>
</tr>
<tr>
<td>T5</td>
<td>252</td>
<td>687</td>
<td>709</td>
<td>1000</td>
</tr>
<tr>
<td>T4</td>
<td>206</td>
<td>592</td>
<td>1396</td>
<td>2083</td>
</tr>
<tr>
<td>T3</td>
<td>314</td>
<td>701</td>
<td>1570</td>
<td>2315</td>
</tr>
<tr>
<td>T2</td>
<td>295</td>
<td>821</td>
<td>1404</td>
<td>1854</td>
</tr>
<tr>
<td>T1</td>
<td>237</td>
<td>460</td>
<td>1270</td>
<td>1629</td>
</tr>
</tbody>
</table>
Irrigation treatment T3 received 80% of the theoretical peppermint water requirement and had the highest LA value. Level T5 with 110% of the water requirement had the lowest final LA value (Figure 9). The depressed effect in level T5 was observed from Period 2 on (Fig. 9). This may be caused by nutrient lixiviation from the shallow root zone and a depletion of the oxygen concentration resulting from excess water. Both of these conditions can have a cumulative negative effect on peppermint leaf area.

4.5 Stress Degree Day

The concept of the stress-degree-day (SDD), the difference between canopy and air temperature measured at the time of maximum canopy temperature, was introduced by Jackson et al. (1977).

\[ SDD = \text{canopy temperature} - \text{air temperature} \] (4.3)
If SDD is negative, the plants are well-watered and transpire freely. But a positive value indicates water stress (Figure 10). The SDD was calculated for 1300 PST corresponding to the time of maximum canopy temperature during the day. Table 12 shows negative values were obtained for Day 1 after irrigation. Only level T5 had a negative value for Day 2 after irrigation. The high positive value obtained by level T2 and level T1 on Day 4 after irrigation shows a clear gradient from level T5. There is also a clear change at level T1 from Day 1 to Day 4 after irrigation. Both trends demonstrate a clear response of the plant to the soil water changes.
Figure 10. Values of stress degree day during the day for the five irrigations levels

Table 12. Values of stress degree day °C

<table>
<thead>
<tr>
<th>DAY</th>
<th>Irrigation Treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T5</td>
</tr>
<tr>
<td>DAY 1</td>
<td>-1.79</td>
</tr>
<tr>
<td>DAY 2</td>
<td>-.77</td>
</tr>
<tr>
<td>DAY 3</td>
<td>3.35</td>
</tr>
<tr>
<td>DAY 4</td>
<td>4.15</td>
</tr>
</tbody>
</table>
The relationship between LA and SDD shows that a more negative SDD did not necessarily imply a larger foliar area. Table 12 shows that the SDD was negative for all treatments during the first day and only level T5 had a negative value for the second day.

4.6 Crop Water Stress Index

The crop water-stress index (CWSI) adds broader applicability to the SDD concept by incorporating the vapor pressure deficit. Canopy temperatures are dictated by the water status of the plants and by ambient meteorological conditions. The Crop Water Stress Index (CWSI) combines these factors to yield a measure of plant water stress (Jackson et al. 1988).

Idso’s method requires the field measurement of $\Delta t$ for a well-watered crop as a function of vapor pressure deficit (Idso et al., 1981A). This provides the lower baseline for a non-stressed crop. The upper limit for $\Delta t$, for an extremely stressed crop, depends on air temperature but is independent of the vapor pressure deficit (Jackson et al. 1988). Calculation of the CWSI initially requires
development of an upper and lower baseline to delimit high water stress and well watered conditions. These limits are calculated using the following equation suggested by Jackson (1988):

\[
\Delta t = \frac{R_n r_a}{\rho c_p} \left( \gamma \frac{1 + \frac{r_c}{r_a}}{\delta + \gamma \frac{1 + \frac{r_c}{r_a}}{\delta + \gamma \frac{1 + \frac{r_c}{r_a}}}} \right) - \frac{e_s - e_a}{\delta + \gamma \frac{1 + \frac{r_c}{r_a}}{\delta + \gamma \frac{1 + \frac{r_c}{r_a}}}} \quad (4.4)
\]

where:

\( \Delta t \) = canopy temperature minus air temperature (\( ^\circ C \))

\( r_a \) = aerodynamic resistance (s m\(^{-1} \))

\( R_n \) = net radiation (W m\(^{-2} \))

\( \rho \) = air density (kg m\(^{-3} \))

\( c_p \) = specific heat of air at constant pressure (J kg\(^{-1} \) C\(^{-1} \))

\( \gamma \) = psychrometric constant (Pa C\(^{-1} \))

\( r_c \) = canopy resistance (s m\(^{-1} \))

\( \delta \) = slope of saturate vapor pressure-temperature relation (Pa C\(^{-1} \))

\( e_s \) = saturated vapor pressure (Pa)

\( e_a \) = vapor pressure of the air (Pa)
For the upper limit with a high water stress state, $r_e$ approaches $\infty$ equation [3] becomes:

$$\Delta t = \frac{R_n}{\rho C_p}$$

(4.5)

When there is no water stress, the plants may behave as a free water surface and $r_e$ can be set at 0. Equation [3] becomes:

$$\Delta t = \frac{R_n}{\rho C_p} \cdot \gamma \cdot \frac{e_g - e_a}{\delta + \gamma}$$

(4.6)

Equation [5] provides a hypothetical lower baseline and is a linear relation between $\Delta t$ and vapor pressure deficit, when $R_n$, $r_a$, and air temperature are held constant. The maximum $R_n$ measured at the experimental site was 555 W m$^{-2}$ while $r_a$ was assumed to be 10 s m$^{-1}$ (Jackson et al. 1988). The temperature used for these calculations was the average air temperature measured at the site, 27.3 C. The calculation of $\delta$ and $\gamma$ was done using methods proposed by Cuenca (1990).
With these computations, the upper limit for $\Delta t$ was set at 5.5°C and the equation for estimating the lower line was:

$$\Delta t = 1.21 - 3.67Vpd \quad (4.7)$$

where: vapor pressure deficit is in kPa and $\Delta t$ is °C.

Figure 11 shows the computed upper and lower baselines and a field observation sample (point B) at $\Delta t = -3$ and a vapor pressure deficit of 2.5 kPa. Point C is -8°C, representing the $\Delta t$ at which there is no water stress. The matching highly stressed condition is point A where $\Delta t = 5.5$. The CWSI is:

$$\frac{B-C}{A-C} = \frac{(-3)-(-8)}{(5.5)-(-8)} = 0.37 \quad (4.8)$$

The CWSI is an approximation of the ET deficit as follows:
Figure 11. Theoretical upper and lower baselines.

$$CWSI = 1 - \frac{ET}{ET_p}$$  \hspace{1cm} (4.9)

where: \(ET\) = evapotranspiration

\(ET_p\) = potential evapotranspiration.

Since the CWSI is an estimate of the ET deficit, a CWSI of 0.37 fits to an ET rate of 0.63 of the ET\(_p\). The theoretical baselines used for computing the CWSI are
limited because air temperature, aerodynamic resistance, and net radiation are estimated as constant. While these variables are assumed to be constant, daily CWSI measurements were done under variable conditions. Furthermore, the assumption that a well-watered crop has a canopy resistance to vapor transport \( r_c \) of 0 s m\(^{-1}\) could be challenged particularly in treatments T3, T2, and T1. High evaporative demands, even when soil water content is high, can cause temporary ET deficits (Hsiao, 1983).

The upper and lower baselines shown in figure 11 are based on field data. The upper baseline with \( \Delta t = 6.6 \) is an average of treatment T1 at 1300 PST on the fourth day after irrigation. The lower baseline was fitted using the data from level T5 on the first day after irrigation from 900 to 1500 PST as follows:

\[
\Delta t = 1.32 - 0.98V_{pd} \tag{4.10}
\]

The correlation coefficient, \( r^2 \), for this relation is 0.68, with the data shown in figure 12.

Figure 12 shows that, many observations fell below the lower baseline, making the CWSI a negative value. The benefit of the field measured lower limit is that it smooth
the average conditions for those terms set to a constant for the theoretical lower limit reviewed earlier. The other advantage is that all measurements of plants with less value than the theoretical baseline will be compared to a field-measured, well-watered baseline, rather than a theoretical lower limit which may be much lower than the field-measured lower limit.

When solar radiation is near the maximum, at 1300 PST, the CWSI values are at maximum values and exhibit differences between irrigation treatment levels. Less available water was related to higher CWSI values and corresponds to the gradient of the treatments (Figure 13).

Since level T3 had highest leaf area, its CWSI average during the period between irrigations is shown in Figure 14. The 1300 PST CWSI for level T3 shows a gradual increase with time indicating potential applicability for irrigation scheduling. Level T3 had a larger Δt level T5 and level T4 but a greater yield. This may be explained by the theory of the "Thermal Kinetic Window" that suggests that each crop has its specific optimum physiological temperature. When a crop is above or below its TKW, its growth is affected (Burke et al. 1988).
Figure 12. Nonstressed baseline.
The CWSI values for level T1 was consistently highest, with maximum values of 1. Greater CWSI values developed for plots at the level T1 of applied water as compared to the levels T5 and T4. There were only small differences in the CWSI between the level T5 and level T4 treatments. Minimum midday CWSI values were about 0.4 with a range of midday values of only 0.3 for the five irrigations levels.
Idso et al. (1981) evaluated CWSI for alfalfa cultivated at different water levels and reported well-defined differences between the treatments in agreement with the results of this peppermint experiment. Sharrat et al. (1983) measured ET rates through the day with a portable chamber and showed curves similar to the peppermint experiment CWSI curves where ET rates were very low early in the day. Analogously, Idso et al. (1982) presented diurnal curves of CWSI which reached a maximum at about 1400 hours for cotton. Wanjura et al. (1984) showed diurnal curves for
cotton where the differences between irrigation treatments were obvious.

Figure 15 shows the relationship between the seasonal ET deficit (1 - ET/ETm) and the CWSI with a comparison to the hypothetical 1:1 relationship. ETm is the maximum seasonal evapotranspiration for the well-watered plots and was assumed equal to ETp, due to the lack of peppermint information. The slope of the regression line was equal to 1.6, while the intercept was -0.63.

![Figure 15. ETd by water balance vs. CWSI.](image-url)
The amount of unexplained variation ($r^2$) was as low as 0.98 which shows that the CWSI can be a significant indicator of ET deficit. However, the CWSI is dependent on an empirical adjustment, related with the weather variation and changes in perennial crops which would vary between years and crop species. The relationship between deficit and CWSI is more meaningful when $ET_m$ is known. The equation fitted was:

\[
1 - \frac{ET}{ET_m} = -0.63 + 1.6CWSI
\]  

(4.11)

Development of a relationship closer to 1:1 between ET deficit and CWSI could occur from refinements in the upper and lower base-lines. Recomputing the base-lines each time the canopy temperature was measured for any experimental plot would improve accuracy. This would require a more accurate measurement of the minimum midday value for canopy resistance to vapor transport ($r_o$) of a non-stressed crop and measurement of net radiation, aerodynamic resistance, vapor pressure deficit, and air temperatures. Improved base-lines would be expected to result in CWSI values closer to 0 from the well-watered plots.
Figure 16 shows the LA deficit \((1 - \frac{LA}{LA_m})\) where \(LA_m\) is the leaf area from the best treatment, as estimated by the experimental CWSI. The correlation coefficient, \(r^2\), for this relation is 0.77. The fitted equation was:

\[
1 - \frac{LA}{LA_m} = 5.39 - 19.22CWSI + 17.28CWSI^2 \quad (4.12)
\]

The high \(r^2\) for LA deficit vs. CWSI indicates the potential usefulness of remotely sensed canopy data for the estimation of crop production, but the problem is how to estimate or measure the Vpd remotely.

4.7 Leaf water stress.

Figures 17 and 18 illustrate diurnal distribution of leaf water stress (PS). No pattern was found among days or periods. The diurnal variation of PS increases from predawn to midday and decreases in the afternoon. All this variation is controlled by climatic conditions rather than
Figure 16. LA deficit as function of CWSI.

plant or soil conditions (Dickey, 1982; Weatherley, 1976). The high diurnal variation of PS in different soil water conditions made it impossible to use the pressure bomb at this time of day. Figure 17 shows the values of PS under different conditions of irrigation. This figure shows that plants under different conditions can reach the same values of leaf water stress.

A sensitivity analysis of the performance of the pressure bomb graphically compares the PS values of two extreme conditions of soil moisture, a well-watered
treatment, level T5, plus its standard deviation and the less-watered treatment, level T1, minus its standard deviation. Figure 18 shows the intersection of those curves as a zone in which points of very different conditions have the same leaf water stress whether from a well-watered condition or less-watered condition. This analysis does not include values of level T2, level T3, or level T4 that had intermediate average values between levels T5 and T1. These results point to the inaccuracy of PS as a predictor of different plant water conditions for mint. Figure 19 shows that during the afternoon level T1 had average PS values higher than level T5.
Figure 17. Average plant stress distribution.
However, figure 19 also shows no intersection of the data at predawn. This points to the usefulness of leaf water stress predawn data: As found by Dickey (1982) and Wheatherley (1976) predawn leaf water stress is a function of the matrix potential only with the plant working like a tensiometer. Figure 20 shows the relationship between soil humidity and PS at predawn. This is expressed as:
Figure 19. Intersection between level T5 and level T2.

\[ PS = \left( -0.01484 + 0.006096 SMC \right)^{-1} \]  

(4.13)

where SMC is soil moisture content.

with \( r^2 = 0.61 \).

This result shows that the predawn PS can be used as a good indicator of soil plant water status. The plant more fully integrates conditions in the active root zone than devices such as tensiometer, neutron probes psychrometer,
Figure 20. Plant water tension curve.

and gypsum blocks which only obtain data from a fraction of the root zone. Predawn PS readings use the plant as a tensiometer. The range over which plants react is 0 - 20 bars or more instead of the 0 - 1 bar range limit of a hydraulic tensiometer.
5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The objective of this study was to test the performance of measurements of infrared canopy temperature and leaf water potential for irrigation scheduling. Both methods were tested under diurnal weather conditions, various soil water content levels and over the growing season. This study shows that both instruments may be applied in irrigation scheduling under specific conditions.

5.1.1 Infrared Canopy Temperature

It is possible to get an appropriate non-stressed baseline for the difference between canopy temperature and air temperature using data from well-watered plants. The crop water stress index (CWSI) is determined using this baseline together with the vapor pressure deficit. The
results of this study indicate that the CWSI measured at midday can be used for irrigation scheduling.

The CWSI represent a combination of the thermal and water status of the plant. This study shows that a low CWSI does not necessarily represent optimum plant growth conditions. The results of this study indicate some point of optimal growth temperature and some negative condition on plants with excessive irrigation. Yield or growth of a plant in good thermal condition (low CWSI) may be diminished for reasons other than water stress such as nutritional deficiencies or diseases. Such situations cannot be detected directly by the CWSI. This study shows that it is possible to predict the yield using a ratio between the CWSI and some yield parameter. However this prediction is based on specific data and can only be used for a crop under similar environmental and management conditions as the base or reference crop.

The relation of leaf area yield and CWSI in peppermint was described by a quadratic function. From several diurnal measurements of CWSI, it was found that maximum CWSI were higher in less-irrigated plots than in well-watered plots. Although the CWSI can indicate differences between irrigation levels, application of CWSI data is not directly useful. Interpretation of CWSI values can be obtained from the relation between the best yield irrigation treatment and its CWSI. However, the difficult question is how much water
to apply to the plants and this question is not answered by the CWSI.

5.1.2 Leaf Water Potential

This study shows that the leaf water potential varied during the day in such a way that it was not possible to establish a relation with water stress, differences in soil moisture content, or different irrigation levels. Leaf water potential was influenced by the daily weather conditions and represented the actual demand more than the cumulative demand or the crop water demand. Therefore midday pressure bomb measurements cannot be used in irrigation scheduling. Predawn measurements of leaf water potential were stable providing reasonable correlation with the different irrigation levels and soil moisture content and therefore may be useful in irrigation scheduling.
5.2 Recommendations for Future Research

The accuracy of the irrigation scheduling by infrared canopy temperature and leaf water potential can be improved by the following recommendations.

1. The CWSI needs to be calibrated against an accurate method of actual ET measurement such as those made using lysimeter, the Bowen ratio, or the pan evaporation method.

2. It is necessary to establish a standard method of determination of the upper baseline which represents a stressed status of the plant. The upper baseline should be within the range where there is no significant loss of yield or unrecoverable changes in the physiology of the plant.

3. The wind speed influences the aerodynamic resistance and effects the mixing of air of different temperatures. For this reason, it is recommended to establish the upper limit on wind speed where the CWSI remains reliable.

4. Instead of determining a baseline for different environmental conditions and stages of growth, the results of this research suggest the study of the optimum specific leaf temperature for each crop related to its physiology and yield production. This parameter could be used as a thermal baseline for irrigation.

5. Measurements of leaf water potential for peppermint need to be calibrated against more accurate methods such as
the thermocouple psychrometer to achieve if the pressure bomb provide an accurate measure of plant stress. It is also necessary to determine other components of the leaf water potential such as osmotic and matrix potential.

6. It is necessary to extend measurements of predawn leaf water stress to three or more readings before sunrise to get a better representation of the equilibrium non-transpiring plant water potential.
6 BIBLIOGRAPHY


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7.1 List of acronyms

CWSI = Crop water stress index
\( \Delta t \) = Canopy - air temperature
ET = Evapotranspiration
SDD = Stress degree day
ET\(_d\) = Evapotranspiration deficit
ET\(_p\) = Potential evapotranspiration
TMK = Thermal kinetic window
Km = Michaelis constant
TSI = Thermal stress index
USDA = United States Agricultural Department
PST = Pacific standard time
7.2 List of symbols

$R =$ radiation
$\varepsilon =$ emissivity
$\sigma =$ Stefan-Boltzmann constant
$T =$ temperature
$r_s =$ aerodynamic resistance
$R_n =$ net radiation
$\rho =$ air density
$c_p =$ specific heat of air at constant pressure
$\gamma =$ psychrometric constant
$r_c =$ canopy resistance
$\delta =$ slope of saturate vapor pressure-temperature relation
$e_s =$ saturated vapor pressure
$e =$ vapor pressure of the air
$\Psi =$ leaf water potential