EVALUATING THE EFFECT OF MOISTURE STRESS ON TOMATO USING NON-DESTRUCTIVE REMOTE SENSING TECHNIQUES.

BY

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A MINI-DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN AGRICULTURE (REMOTE SENSING)

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FACULTY OF SCIENCE AND AGRICULTURE,

UNIVERSITY OF LIMPOPO

APRIL 2009

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Declaration

I declare that the mini dissertation, I hereby submitted for the degree of Master of Science in Agriculture (Remote Sensing) at the University of Limpopo, is my own work and has not been previously submitted by me for the degree at another Institution.

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M. N Mushia

ACKNOWLEDGEMENT

I would like to thank God the father of our Lord Jesus Christ for the guidance and wisdom He gave me towards accomplishing my studies. I will also want to give my sincere regards and words of gratitude to my supervisors Mrs. P. Shaker and Prof. H.A Shimelis for their patience, guidance and for support they gave me during my study. Mr. Ramalema S.P is thanked for helping me with statistical analysis.

I would like to give my regards to my friend and colleague Mr. Bodirwa K. B and my best friend Ms. Mogano M.A for being with me throughout the entire study, without your help this paper wouldn't have been completed, you have been so supportive and encouraging. Thanks go to Mr. Motubatse M.R and Mr. Mohlala J.P for their words of encouragement when I really needed them.

Lastly I would like to thank my mother Moshia M.L, my grandmother Moshia M.M, brothers and sister for compromising a lot to support me through everything, thank you for patience and your care. I would also want to thank the University of Limpopo and National Research Fund (NRF) for all support and funding during the course of my studies.

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Definitions, Abbreviations and Key words

a. Abbreviations

1. NDVI- Normalize Differential Vegetation Index
2. NF- Number of fruits per plant
3. FY- Fruit yield per plant
4. PH- Plant height
5. DT50%F- Days taken for 50% flowering
6. C.V- Coefficient of variance
7. LSD- Least Significant Difference

b. Definitions

1. Days taken for 50% flowering- days taken for 50% plants to flower (Lafitte *et al*., 2002).
2. 50% fruiting stage- when 50% plants have bore fruits.
3. Stressed plants- watered after every 5 days with an amount of 500ml per pot until 50% flowering stage after that they were watered after every 3 days with the same amount of water until harvest (www.essortment.com).
4. Non-stressed- watered with an amount of 500ml per pot after every 3 days until at 50% flowering stage after that they were watered daily with the same amount until harvest (www.essortment.com).

c. Key words

1. Roma VF
2. Flora Dade
3. Field conditions
4. Greenhouse conditions

ABSTRACT

The aim of this experiment was to evaluate the effect of moisture stress on tomato, using non-destructive remote sensing techniques and agronomic traits under field and greenhouse conditions. Two tomato cultivars *Roma VF* and *Flora Dade* were used for the trial. The soil was fertilized optimally for all nutrients to avoid other stresses except water stress; a 2x2 factorial experiment was conducted using two levels of water regimes (stressed vs. control (non-stressed)) having four replicates and two cultivars using a Completely Randomized Design. Pots were put under greenhouse and field conditions. Canopy temperature was measured using an infrared thermometer, NDVI values were recorded using a green seeker hand-held optical sensor unit and stomatal opening were determined using a leaf porometer. Other agronomic traits including days taken for 50% flowering, plant height, number of fruits per plant and fruit yield per plant were recorded.

Leaf temperature in stressed plants was high as compared to non-stressed plants, whereas NDVI and stomata conductance values were low. Number of fruits per plant was low; each plant had 4.00 fruits under field conditions and 5.00 fruits per plant under greenhouse conditions as compared to 9.00 fruits under field conditions and 13.00 under greenhouse conditions for non stressed plants. Stressed plants were shorter as compared to non-stressed plants and days taken for 50% flowering were delayed in both cultivars for stressed plants. Stressed plants showed a sign of stress at early stages of plant development. Most of these signs were found on the plants rather than on the fruits, the shape of the main stem of a growing plant was one of the good indicators as it became thin and stringy under stressed conditions. The experiment showed that it is possible to evaluate the effect of moisture stress on tomato by the use of canopy temperature, NDVI, stomatal conductance and agronomic traits.

CHAPTER 1

INTRODUCTION

1. Background

The term remote sensing is usually restricted to instruments that measure electromagnetic radiation reflected or emitted from an object. The techniques for recording information in non-contact sensing include: cameras with films and filters in differing combinations; specialized electronic instruments like radiometers, video systems etc, and various platforms at different heights above the vegetation canopies. The object can be analyzed many times non-invasively and without damage. The specific properties of vegetation, healthy or diseased, influence the amount of radiation reflected from the leaves. The remote sensing can thus be used as a means of detecting and assessing changes in plant canopies (Nilson, 1995).

Remote sensing can act as both a potential production tool and a method for large-scale verification of research on crop growth characteristics (Plant *et al*., 2000). Full –season crop monitoring techniques can help farmers to produce a quality crop and make management decisions for the following years. However, for remote sensing to be effective for in-season management decisions, it must provide a quick, accurate method for identifying crop growth characteristics and detecting stress events. Detecting subtle changes in soil and/or crop properties indicative of impending change requires spatial and temporal resolution unachievable by most monitoring strategies.

Remote sensing can be a very useful tool to predict crop growth, yield, water stress, and also soil and crop characteristics. Several studies have examined technologies involving remote sensing to quantify water stress (Bowman, 1989; Penuelas *et al.,* 1993). Moran *et al*. (1989) investigated the effect of water stress on canopy architecture in tomato and the sequential effect on canopy

temperature. They found water stressed canopies to have a lower spectral reflectance in the NIR (Near infrared) and red wavebands when compared with unstressed canopies. Other studies estimated leaf water status by measuring reflectance spectra. Carlson *et al*. (1971), Gausmann *et al*. (1971) and Hunt *et al*. (1987) analyzed the relationship between reflectance spectra and leaf water status in numerous plant species, and pointed out the possibility to estimate relative leaf water content by reflectance at specific wavelengths in the range of the near-infrared. Work by Brix (1979) with tomato showed that the reflectance in the infrared spectra (810, 1665, and 2210 nm) increased as relative water content decreased.

Remote sensing techniques can provide detailed, spatially distributed information on crop growth and condition for individual field or many fields within an agricultural region. Such information can be useful in a variety of applications, including directing precision farming activities and estimating crop production. For most of these applications, one must interpret the remotely sensed data (usually in the form of surface reflectance) in terms of some plant canopy physical characteristic (such as present land cover) that is indicative of the state of the crop. One popular approach that has been applied to many different crops has been the development of empirical relationships between remotely sensed and observed plant canopy data. In this approach a mathematical curve is statistically fitted to a set of paired measurements of surface reflectance and the plant canopy characteristic of interest. The success of this approach is dependent on the ability to collect one or more field data sets of sufficient quality to support a robust fit between the remotely sensed and plant canopy measurements (Maas, 1998).

Factors influencing leaf optical properties include anatomical structure of the leaf, leaf age, leaf water content and mineral deficiencies. Near-infrared reflectance is strongly influenced by anatomical structure. It depends on the number of cell layers and the relative thickness of the spongy mesophyll. Thus, the leaves of the dicotyledons have higher reflectance than those of the monocotyledons having

the same thickness, because their spongy mesophyll is more developed. Leaf optical properties change significantly only during the juvenile stages and senescence. During the major part of their life the leaves of the plants have practically constant optical properties. Leaf water content has an indirect effect on the visible and near –infrared reflectance spectrum. Thus, a decrease in leaf water content induces an increasing reflectance in the whole spectrum (Guyot, 1990).

Various types of plant stress have been identified using remote sensing techniques. These include disease detection, water stress and nutrient stress (Fouché and Booysen, 1994). Techniques to more accurately quantify crop evapotranspiration (ETc) are needed for determining crop water needs and appropriate irrigation scheduling. It has been found that different spectral regions are useful for the detection of plant water stress. One is the near infrared (NIR) 0.7 -1.3 μm region characterized by high wavelength caused by multiple reflectance and scattering of light in the spongy mesophyll structure of plants (Horler and Barber, 1981; Jackson, 1986; Ripple, 1986). Second is the mid infrared (MIR) 1.3-3.0 μm region dominated by strong water absorption bands (Everitt *et al.,* 1987a; Grant, 1987; Escobar *et al.,* 1988) and directly affected by leaf water content (Tucker, 1980; Grant, 1987). Third is thermal infrared radiation, 8 to 14 μm, of the plant canopy as a whole (Jackson *et al*., 1977 Jackson, 1982; Fouché, 1993). As water becomes limited, transpiration is reduced and leaf temperature increases above the air temperature because of the absorption radiation.

Availability of water is one of the most limiting factors in crop production. Over the past years, the increased use of irrigation and concern over groundwater resources has brought about an awareness of efficiently utilizing water resources. So far direct plant based measurements are limited to leaf water potential by pressure chamber, stomatal conductance by porometer, and canopy temperature by infrared thermometry. These measurements are time-consuming and require a number of observations to characterize a whole field (Jackson,

1982). Because of limitations to the above methods, it would be beneficial to use remote sensing techniques to help farmers to determine when and/or where a water stress exists and additionally to predict possible yield losses. Early detection of a water stress could trigger irrigation before yield loss occurs.

So far a lot of investigations focused on the development of spectral indices for the detection of water stress. The results indicated that the relationships e.g. NIR/red and NDVI (Normalized Differential Vegetation Index) might be useful for estimating the subsequent need for irrigation. Jackson *et al.* (1983) used several ratios and wavelength bands and determined that water stress could not be detected until after there was a stress-reduced retardation in growth. The ability of these ratios to detect water stress depends on plant growth stage, soil background, and atmospheric changes. Further more, these reflective indices might not differ from those of other stresses (Tarpley *et al.,* 2000) thus indicating a lack of selectivity and consequently a decrease of accuracy in predicting the water status of plants.

Tomato (*Lycopersicon esculentum*) is the second most important vegetable crop next to potato. Tomato is a rapidly growing crop with a growing period of 90 to 150 days. It is a day length neutral plant. Optimum mean daily temperature for growth is 18 to 25ºC, with night temperatures between 10 and 20ºC. Larger differences between day and night temperatures, however, adversely affect yield. The crop is very sensitive to frost. Temperatures above 25ºC, when accompanied by high humidity and strong wind, result in reduced yield. Night temperatures above 20ºC accompanied by high humidity and low sunshine lead to excessive vegetative growth and poor fruit production. High humidity leads to a greater incidence of pests and diseases and fruit rotting. Dry climates are therefore preferred for tomato production.

Tomato can be grown on a wide range of soils but a well-drained, light loam soil with pH of 5 to 7 is preferred. Waterlogging increases the incidence of diseases such as bacterial wilt. Field tomatoes are a long season crop with high water

requirements. An average cultivar requires about 40 cm (15.7 in) of water over the growing season, with the need for moisture increasing until full fruit load is developed. The most critical times for moisture are during flowering, fruit set, and fruit sizing.

Tomatoes are more tolerant of moisture stress than crops such as pepper and cucumber. They can adjust their physiological processes to conserve water while maintaining some growth. Early exposure to moisture stress makes the plant more tolerant of moisture stress later in the season. While this allows the tomato plant to survive where some crops would suffer irreversible damage, prolonged water stress does reduce yield as the plant uses energy to make these adaptations (LeBoeuf, 2006).

Although the plant can survive dry conditions, optimal yield and quality will not be achieved. Irrigation of tomatoes can result in higher and more consistent yields, better quality, less blossom-end rot, and less cracking. Research on plant responses to stress in tomato has been limited (Sheldrake and Saxena, 1979; Keatinge and Cooper 1984; Leport *et al*., 1999). Keeping these considerations in view the present investigation was undertaken to study the influence of moisture stress on the two types of tomato (Roma VF and Flora Dade) grown throughout the world.

The main consequence of moisture stress is decreased growth and development caused by reduced photosynthesis. Photosynthesis is the process in which plants combine water, carbon dioxide and light to make carbohydrates for energy. Chemical limitations due to reductions in critical photosynthetic components such as water can negatively impact plant growth. Low water availability can also cause physical limitations in plants. Stomata are plant cells that control movement of water, carbon dioxide, and oxygen into and out of the plant. During moisture stress, stomata close to conserve water. This also closes the pathway for the exchange of water, carbon dioxide, and oxygen resulting in decreases in photosynthesis. Leaf growth will be affected by moisture stress

more than root growth because roots are more able to compensate for moisture stress (Bauder, 2003). The purpose of this experiment was to evaluate the effect of moisture stress, using non-destructive remote sensing techniques and agronomic traits in tomato under field and green house condition.

CHAPTER 2

LITERATURE REVIEW

2.1 Canopy temperature

Water deficit is one of the most important factors limiting crop yield, and the monitoring of crop water status is important for reasonable irrigation and water saving cultivation. Using crop canopy temperature to characterize crop water status is a new method for the monitoring. Tanner (1963) first evaluated crop canopy temperature with an infrared thermo-detector to monitor crop water content. It has been found that canopy temperature was usually lower than air temperature under sufficient soil water conditions except noontime in wheat, maize and other dryland crops, and the daily changes in canopy-air temperature difference were gentle, while under water-deficit conditions, the canopy-air temperature difference varied largely, especially in the afternoon. Cai and Kang, (1997) constructed a statistics equation about cotton canopy-air temperature difference with solar radiation intensity, relative humidity and the soil water content for determining the irrigation index.

The most established method for detecting crop water stress remotely is through the measurement of a crop's surface temperature. The correlation between surface temperature and water stress is based on the assumption that as the crop transpires, the evaporated water cools the leaves below that of air temperature. As the crop becomes water stressed, transpiration will decrease, and thus the leaf temperature will increase (Jackson, 1982). Other factors need to be accounted for in order to get a good measure of actual stress levels, but leaf temperature is one of the most important. Because a major role of transpiration is leaf cooling, canopy temperature and its reduction relative to ambient air temperature is an indication of how much transpiration cools the leaves under a demanding environmental load.

The relationships among canopy temperature, air temperature, and transpiration are not simple. They depend on atmospheric conditions (vapor pressure deficit, air temperature, and wind velocity), soil conditions (mainly available soil moisture), and plant characteristics (canopy size, canopy architecture, and leaf adjustments to water deficit). Relatively lower canopy temperature in water stressed crops indicates a relatively better capacity for taking up soil moisture or for maintaining a relatively better plant water status.

Researchers have found lower canopy temperature to be correlated with final yield under stressed conditions when canopy temperature was measured near flowering. Canopy temperature is affected by the relative amount of desiccated and dead leaves in the canopy and the studies show that it can be positively correlated with leaf death score (Garrity and O`Toole, 1995). For canopy temperature to represent differences in drought tolerance, measurements must be made when the population is under water deficit, as seen by some leaf rolling at midday.

Infrared thermometers are instruments that can be used to measure a crop's surface temperature remotely. The thermal infrared spectral region of 8 to 13 µm is typically used for thermal remote sensing. This spectral range contains the maximum thermal emission for temperatures in the range found at the earth's surface and is less subject to absorption by atmospheric gases. Emissivity in the above equation represents how efficiently the surface emits energy. A perfect emitter (called a "blackbody") has an emissivity of 1, and plant leaves have emissivity values that typically range between 0.97 - 0.98. Assuming an emissivity of 1 for plants will usually result in less than 1^{o}C error; however, some soil surfaces can have emissivity of 0.93, which can result in more significant errors in apparent temperature.

In 1977, Idso *et al*. and Jackson *et al*. used infrared thermometers to measure canopy temperatures. By subtracting the air temperature from the canopy temperature, the stress Degree Day (SDD) equation was developed (Jackson *et*

al., 1981). This equation was developed as a possible irrigation-scheduling tool using the thermal infrared thermometer as the main sensor. Geiser *et al.* (1982) aligned the canopy minus air temperature with net radiation and vapour pressure data to use as an irrigation-scheduling tool. Gardner *et al.* (1981) suggested that canopy temperature and plant water potential are correlated, but not linearly.

The advancement in the state of the art in infrared technology the past years has brought about the production of lightweight, hand held infrared thermometers. These operate in the 8-13 micrometer thermal spectrum and can measure plant canopy temperatures accurately and rapidly. Some of the shortcomings of the IR thermometer are that its field of view is restricted to its distance from the subject of measurement. On ground level at a height of 1 m from the crop canopy, only areas of roughly 25mm × 25mm is measured (Fuchs, 1990). To cover a large area of 50 ha, many measurements have to be made and this can take a long time. A further difficulty is measuring the canopy temperature of row crop at early stages (Howell *et al.,* 1984) and the fact that canopy temperature based irrigation scheduling, allows determination of irrigation timing but not amounts (Nielsen, 1990). Therefore standardization of, and consistency in, the procedure is important.

For many years the concept of using canopy temperature to detect the onset and duration of plant water stress has been known (Tanner, 1963; Wiegand and Namken, 1966; Ehrler and van Bavel, 1967; Aston and van Bavel, 1972; Bartholic *et al.,* 1972; and Ehrler, 1973). When a leaf is freely transpiring, the cooling properties of the evaporating water keep the leaf temperature below that of the air. When plant water intake becomes deficient as when soil moisture content is low, the heat load of the leaf builds up because convection and thermal radiation are insufficient to dissipate the heat load. Thus, the leaf temperature will approach and often rise above air temperature when soil moisture content is low.

Clawson and Blad (1982) concluded that canopy temperature variability can be used to signal the onset of plant water stress in maize but that the severity of the stress is better indicated by the magnitude of the elevation of the average canopy temperature above that of a well watered reference plot. Geiser *et al*. (1982) showed that the approach of Slack *et al.* (1981) could reduce the water applied to maize plots (as compared to irrigation scheduling by a checkbook method)

Accordingly, a few have used canopy temperatures to schedule irrigation whereas others have alluded to the possibility of using canopy temperature as an irrigation-scheduling tool. Generally, the art relating to irrigation scheduling based on canopy temperatures is in its infancy and is begging for more effective, practical and efficient systems and methods for scheduling irrigation.

2.2 Vegetation Indices (NDVI)

The Normalized Difference Vegetation Index (NDVI) has been widely used for remote sensing of vegetation for many years. This index uses radiances or reflectance from a red channel around 0.66 μm and a near-IR channel around 0.86 μm. The red channel is located in the strong chlorophyll absorption region; while the near-IR channel is located in the high reflectance plateau of vegetation canopies (Kumar and Monteith, 1982). The visible red and near-infrared channels are used to calculate a vegetation index. NDVI represents the difference in absorbance and reflectance in the red wavelengths (RED) and near infrared wavelength (NIR):

NDVI = (NIR – RED) / (NIR + RED)

There is a negative relationship between red reflectance and green biomass, and a positive relationship between NIR reflectance and green biomass (Kanemasu, 1985; Tucker and Seller, 1986). NDVI appears to be almost insensitive to variations in canopy geometry (Tucker, 1979 and Kanemasu *et al.,* 1990). It was found that the reflectance ratio of a crop over a growing season followed the LAI

curve. The ratio increased above unity (ratio equaling 1.0) at a LAI of about 1.0 and remained above unity during maximum growth, then decreased to below unity at maturity (Tucker, 1979 and Kanemasu *et al.,* 1990). Kanemasu *et al*. (1990) found that the relationship between the NDVI and the fraction of solar energy intercepted by a crop is near-linear and appears to be less sensitive to variations in canopy structure and soil background reflectance.

The band ratio indices create new spectral bands that are useful for emphasizing certain physiologically important features of the crop. NDVI was used mostly as one of the few remote sensing techniques to determine tomato irrigation timing and it was found that NDVI decreases as plant water status decreases.

It was found by (Glen *et al.,* 2004) that NDVI decreases as plant water status decreases and also increases as plant water status increases, so in order to avoid over irrigation or under irrigation the NDVI data can be useful and it will also help the farmer for future decision making on irrigation scheduling and also to estimate the crop water requirements since water stress has a high impact on crop yield (Doorenbos and Pruitt, 1977).

Vegetation indices using red (R; 0.65- 0.70 μm) and NIR wavelengths have been successfully used to infer plant water stress and the subsequent reduction of plant productivity (Richardson and Everitt, 1987; Thompson and Wehmanen, 1979; Walsh, 1987; Wiegand *et al.,* 1972). These vegetation indices are highly correlated with total leaf water mass per ground area (Tucker, 1979). However, NIR/R vegetation indices are physiologically related to the canopy chlorophyll content and absorbed photosynthetically active radiation (Asrar *et al.,* 1984; Tucker and Seller, 1986).

Green leaves commonly have larger reflectance in the near infrared than in the visible range (figure 2.1). As the leaves come under water stress, become diseased or die back, they become more yellow and reflect significantly less in

the near infrared range. Vegetation NDVI typically ranges from 0.1 up to 0.6, with higher values associated with greater density and greenness of the plant canopy.

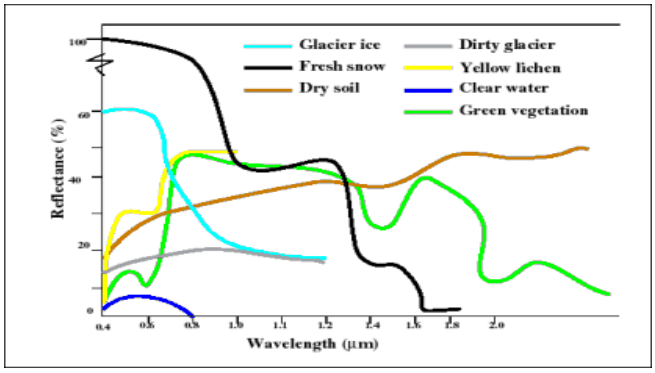

Figure 2.1: Spectral reflectance curves for various natural surfaces by (Aulakh *et al*., 1992).

Temperature response to suddenly induced water stress is faster than changes in NIR reflectance (Jackson and Ezra, 1985). Methods that combine thermal data with NIR and R data, such as in the Normalized Difference Vegetation Index, are significant advances for the detection of regional vegetation water stress (Hope, 1988; Nemani and Running, 1989).

2.3 Moisture availability and moisture stress

The biggest element in the world of agricultural production that makes or breaks a crop is water. The ideal situation for maximum growth is when there is sufficient moisture for the soil to stay moist enough to meet the crop's evapo-transpiration demand (the amount of water being lost from the leaves of the plant). Soil is intricately structured and the amount of water that is available for a plant's use is dependent partly upon the characteristics of the soil and how much water it can hold at any given time (Ratliff *et al.,* 1983).

Most crops can suffer greatly from lack of available water, especially during their most critical stage of development: pollination and fruiting stage. The crop can lose up to 50 percent of its yield due to stunted development during this time period. Average water use for most crops during pollination and fruiting is about

1/3 inch (0.83 cm) per day (Appendix table 8.8). So, for example, with a water storage capacity of 1.8 inches per foot (54.9 cm), a fully charged silt clay loam soil might carry most crops with a three foot (91.44cm) rooting depth up to 18 days during fruiting and early fruiting stages (Wraith and Baker, 1991).

With moisture constantly being available to plants, there will be little incentive for the roots to grow outwards and downwards to find more water. The result is a compact root system, which in subsequent dry conditions is the worst possible situation that can be found. In sunny, hot and windy situations, the rate the plant can get water to the roots is slower than the plants can transpire (or transmit moisture through the leaves). This is when plants begin to wilt. Cloudy, cool days are more advantageous to the plant under such environmental conditions, as transpiration occurs more slowly, so that the soil can more easily supply sufficient moisture to the plant roots (Drissen 1986; Campbell and Diaz, 1988).

Plants are almost completely made up of water so it is important to supply them with adequate water to maintain good plant health. Not enough water and roots will wither and the plant will wilt and die. Too much water applied too frequently deprives roots of oxygen leading to plant diseases such as root and stem rots. The type of plant, plant age, light level, soil type and container size will all influence when a plant needs to be watered (http://www.backyardgardener.com).

Previous work on the effect of water stress on tomato processes and growth have often provided contradictory results because the internal water stress was not measured directly but rather interpreted from soil and atmospheric water conditions. When the crop water stress was measured, it was expressed as content or deficit in amount of water and this was an unsatisfactory basis for comparing water relations of different crops and for studying water movement through the soil-plant –atmosphere. A reliable and convenient remote sensing instrument to make progress in the field of plant water relations measured a suitable index of tomato water stress; this was advocated by Obreza *et al.,* 2001.

A measure of the free energy level of water (water potential or diffusion pressure deficit as it was then called) appeared to be the best single expression of the crop water status. The use of NDVI in water and crop relationships was tested and it was put to use in investigating relationships of leaf water potential and the rates of the physiological processes of photosynthesis and transpiration with increased water stress suggested that the stomatal diffusion resistance was the mechanism by which plant processors were affected.

Rahman *et al.* (1998) carried out an experiment on evaluating the effects of water stress (control, mild or severe) on some physiological and morphological parameters of tomato cultivars TM 0126 and Kyokko and discovered that water stress increased leaf temperature, and decreased photosynthetic rate, stomatal conductance, transpiration rate, leaf water potential, root and shoot dry matter weight and plant height in both cultivars, although differences between cultivars were observed. Root length was significantly longer in TM 0126 than in Kyokko under control, mild and severe water stress conditions. TM 0126 was more resistant to water stress than Kyokko.

In the situation of employing environmental remote sensing, it is necessary to develop universal methods, which can be used for the evaluation of the water status of plants. In addition, the developed methods should be able to distinguish water stress from other stresses. Studies done by Graeff *et al.* (2001) and Osborne *et al.* (2002) have shown that nutrient deficiencies could be identified and quantified by means of reflectance measurements based on selected stress specific wavelength ranges. This study extends the work of Graeff *et al.* (2001) and aims to determine whether reflectance measurements can be effectively used to identify and to distinguish water stress from other plant stresses. Greenhouse studies were used to establish a calibration for the determination of leaf water content in wheat plants by rapid and non-destructive reflectance measurements and to increase the accuracy of irrigation recommendations by clearly distinguishing plant stress factors.

2.4 Reflectance spectra

All of the reflectance spectra of the plant leaf have the same shape. Different spectral domains can be considered according to the different leaf optical properties of the vegetation, a combination of different energy-matter interactions in the visible and near infrared spectra being responsible for the characteristic spectral reflectance of vegetation (figure 2.1) (Collins, 1978; Guoliang, 1989 and Guyot, 1990). The amount of reflectance light, as a percentage of incoming light is usually called the reflectance factor (Nilson, 1995 and Botha, 2001).

In the visible domain leaf reflectance is low (less than 15%). Leaf pigment such as chlorophyll, xanthophylls, carotenoids and anthocyanins absorb the main part of the incident radiation. Chlorophyll does not absorb all the incident sunlight equally. The chlorophyll molecules preferentially absorb blue and red light for use in photosynthesis (as much as 70% to 90% of incident light). Much less of the green light is absorbed (Guyot, 1990 and Campbell, 1996). The interaction of electromagnetic radiation with plant leaves depends on the chemical and physical characteristics of those leaves. The absorption is essentially a function of changes in the spin and angular momentum of electrons, transitions between orbital states of electrons in particular atoms and vibrational rotational modes within polyatomic molecules (Jacquemoud and Baret, 1990).

In the near infrared spectrum, reflection of the leaf is controlled by the structure of the spongy mesophyll tissue. The cuticle and epidermis are almost completely transparent to infrared radiation, so very little infrared radiation is reflected from the outer portion of the leaf. Radiation passing through the upper epidermis is strongly scattered by optical density boundaries within the mesophyll tissue and cavities within the leaf. Very little of this infrared energy is absorbed internally: most (up to 60%) is scattered upwards (reflectance energy) or downwards (transmitted energy). Thus the internal structure of the leaf is responsible for the bright infrared reflectance of living vegetation (Collins, 1978 and Campbell, 1996). Although the enhanced reflectivity in the infrared and the absorption in the

visible spectrum are due to different processes of energy –matter interaction, they are related insofar as chlorophyll production and mesophyll development are interdependent functions of plant growth and vigour (Collins, 1978).

Strong water absorption bands dominate the middle infrared and are directly affected by leaf water content (Tucker, 1980 and Grant, 1987).

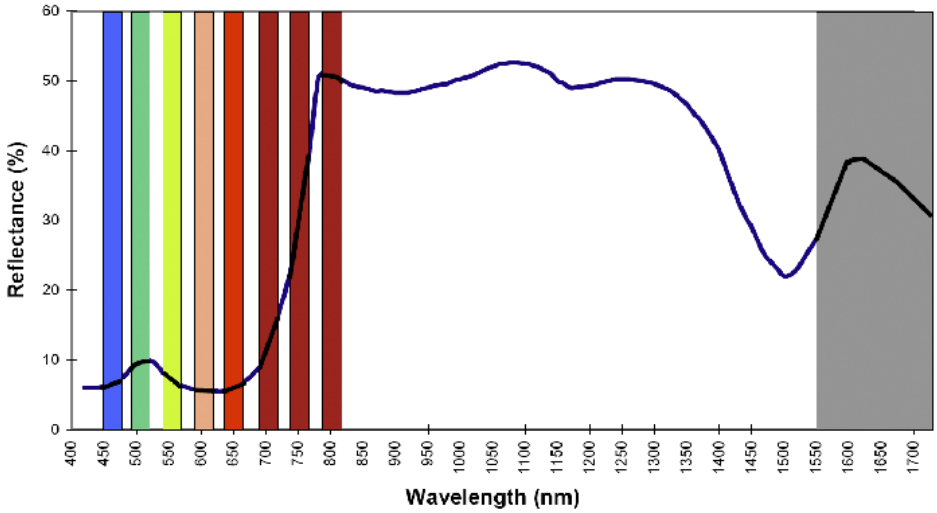

Figure 2.2A typical green vegetation reflectance spectrum superimposed over the spectral bands

2.4.1 Factors influencing spectral reflectance of vegetation

Factors influencing leaf optical properties include anatomical structure of the leaf, leaf age, leaf water content and nutrients. Near-infrared reflectance is strongly influenced by anatomical structure. It depends on the number of cell layers and relative thickness of the spongy mesophyll. Thus, the leaves of dicotyledons have a higher reflectance than those of monocotyledons having the same thickness because their spongy mesophyll is more developed. During the major part of their life the leaves of plants have practically constant optical properties. Laboratory studies of reflectance from single leaves showed that pubescence, growth-regulating chemicals, nutrient supply in the soil, position of the leaf on the plant, thickness and water content, salinity and physiological age of the leaf

affect absorption, transmission and reflection of light by plant leaves, as do several other physiological factors (Leamer *et al.,* 1978). As a plant is subjected to stress by disease, insect attack, moisture, or nutrient shortage, the spectral characteristics of the leaf may change (Campbell, 1996).

2.5 Stomatal conductance

Stomatal conductance is the speed at which water vapor can evaporate from pores (stomata) in the plant's leaves. It depends on the difference in the vapor pressure between the spaces inside the leaf (near the stomata) and the vapor pressure in the air surrounding the leaves.

If the speed of conductance is too great, the plant transpires a lot of water and the soil dries out, placing the plant in water stress. To avoid this condition, plants try to some extent to control the speed of evaporation by closing the stomata when the sun is bright (which is when evaporation is greatest). However, the speed of photosynthesis depends on the plant being able to release the produced oxygen into the atmosphere, so closing the stomata too much or for too long reduces photosynthate production. Therefore, plants keep opening and closing their stomata to keep a middle line between the two constraints (www.gardenwithinsight.com).

CHAPTER 3

Evaluating the effect of moisture stress on tomato using non-destructive Remote Sensing techniques and agronomic traits.

3.1 Introduction

Productivity response to water stress is different for each crop and is expected to vary with the climate. Many factors need to be accounted for in order to obtain a good measure of actual stress levels, but leaf temperature is the most important factor (Smith *et al*., 1985; Stockle and Dugas, 1992). Crop water stress has the major effect on crop production, yield and crop health. It is because of this effect that rapid, low-cost monitoring techniques are required to monitor the water stress. While many field-based techniques have proved suitable, they have sometimes proved problematic in application over large areas of land. For this reason, remote sensing technology (NDVI data by Green Seeker sensor and thermal infrared thermometer) holds considerable potential for the inventorization and monitoring of crop water stress at relatively low-cost (Dreyer, 1990).

Measurement of stress-related variability was investigated in early work by Gardner *et al.* (1981) and Clawson and Blad (1982) and subsequently revisited by Bryant and Moran (1999) and Gonza´ lez-Dugo *et al.* (2000). However, little progress has been made towards quantifying the complex relationship between canopy temperature variability, water stress and the spatial pattern of water availability, particularly the likelihood that the variability in canopy temperature will increase with stress severity. Also, little attention has been given to situations of severe water stress in which transpiration in the field will be greatly reduced, starting at locations with less available water. The canopy temperature variability should then decrease after a certain level of stress has been exceeded. Greater understanding of these interactions would clearly be beneficial for irrigation

scheduling. With recent improvements in accuracy, deployment and spatial resolution of thermal sensors, the use of the variability of remotely sensed canopy temperature deserves further exploration.

Much of the research on assessment of moisture stress on crops has been based on aerial photography and image processing on computer. The purpose of this research was to use non-destructive remote sensing techniques to develop a methodology for monitoring moisture stress. If correlation is found between NDVI data by Green Seeker sensor and thermal infrared thermometer and leaf porometer and moisture stress monitored data a cheaper and rapid method of evaluating the effect for moisture stress could be developed to assist farmers to improve their crop production yield since moisture is one of the major factors that limit production and plant growth.

Tomato is an ideal crop to study as it has been well documented that growth and development can have a strong response to changes in environment during production. For example, canopy temperature is known to significantly effect tomato growth and development. Higher temperatures imposed throughout a tomato crop's development usually result in shorter crop production time, but with smaller fruit and lower yield (Rylski, 1979; Sawheny and Polowick, 1985).The purpose of this investigation was to evaluate the effect of moisture stress, using non-destructive remote sensing techniques and agronomic traits in tomato under field and green house condition.

3. 2 Materials and Methods

3.2.1 Study site and experimental design

The study was conducted at the university of Limpopo, Mankweng area, Limpopo Province, South Africa, situated about 40 km from Polokwane, the capital of the Limpopo Province. The study area is characterized by hot dry summers and cool winters with an annual rainfall from 400 to 500 mm/a. The temperature ranges

from an average minimum of 6°C in winter to an average maximum of 28°C in summer. The location is situated between latitudes 23.46° and 23.48°S and longitudes 29.42° and 29.47°E and lies at an average altitude of 1400 m above sea level.

The study was conducted under two different conditions; the greenhouse conditions and outside the greenhouse (to represent field conditions). Under greenhouse conditions the research was conducted from November 2006 to January 2007 and outside the greenhouse (under field conditions) the research was conducted from September 2007 to January 2008. A 2x2 factorial experiment was conducted using two levels of water regimes (stressed vs. non-stressed) having four replicates and two cultivars using a Completely Randomized Design.

3.2.2 Soil and soil preparation

Soil of the Hutton form (Mac Vicar, 1991) was used in this experiment. The soil was collected at the Syferkuil experimental farm of university of Limpopo. Soil collected was not recently exposed to any fertilizer treatment.

Soil was analyzed for inherently present nutrients (P and K) as well as pH. P was determined using Bray-1 extraction and spectrography, K using ammonium acetate extraction and atomic absorption spectrophotometer and pH was determined using water extraction (Barnard *et al*., 1990). The results of soil analysis are presented in Table 3.1. The fertilizer application was then calculated based on fertilizer requirement of tomato Buys (1991) (Table 3.2).

Table 3.1 Nutrients status of soil sample used in pot trial

P(ppm)	**K(ppm)**	**pH(H_2O)**
17	382	5.92

Table 3.2 Optimum fertilizer requirements of tomato at selected projected yield.

Crop type	Projected yield (t/ha)	Optimum N (Kg/ha)	Optimum P (Kg/ha)	Optimum K (Kg/ha)
Tomato (*Lycopersicon esculentium*)	**35**	**120**	**80**	**30**

Buys (1991)

3.2.3 Pot Trial

The weight of 1 ha of soil at 30cm plough depth was calculated at a soil bulk density of 1.33 g cm^{-3} (Buys, 1991):

100m x 100m x 0.3m (plough depth) x 1333 kg m^{-3} (bulk density) = $3.999x10^6$ Kg/ha

The weight of the soil in one 20cm diameter plastic planting pot used in the trial was 4kg. The ratio of one pot to one hectare was thus calculated to be:

1:999750

Utilizing this ratio for calculation of fertilizers to be applied plastic pots (20cm diameter) with drainage holes at the bottom were filled with soil. Soil was sterilized using autoclaving method (Soil was autoclaved at 121^0C for a minimum of 30 min) before it was put into plastic pots. The soil was fertilized optimally for all nutrients based on tomato fertilizer requirement. The pots were put under controlled greenhouse and field conditions.

Fertilizers used in the pot trials were Urea [$(NH_2)_2CO$]. (46% N), Super phosphate [$Ca(H_2PO_4)_2$]. (10.5% P) and KCl (50% K) (Table 3.3). The fertilizers were weighed into a glass beaker using a Mettler AC100 balance with 0.0001g readability. Distilled water was added and the fertilizer salts were allowed to dissolve. The soil was weighed with Mettler PE 6000 balance with 0.01g readability.

The soil was mixed with the fertilizers by spreading the soil in a black refuse bag and the fertilizer solution (drawn up in a 100ml pipette) was evenly sprinkled onto the soil surface. The bag was closed and the soil and fertilizer solution thoroughly mixed. Coarse sand was put at the bottom of each pot to ensure good drainage. The prepared soil was then added to the pot and lightly firmed.

Table 3.3: Fertilizer for tomato pot trial

Fertilizer	Amount Applied(Kg/ha)	Amount Applied(g/pot)
Urea	260.87	0.2609
Superphosphate	761.91	0.7621
KCl	60	0.060

3.2.4 Instruments used in data collection:

3.2.4.1 Infrared thermometer

The Everest lightweight, hand-held infrared thermometer (figure3.1) was used for measuring the canopy temperature. It has a tenth degree resolution and responds in a fraction of a second over the temperature range of – 25 to 75 degrees Celsius. The emissivity was set at 0.98, which reduces the possibility of taking readings at an incorrect setting. The infrared thermometer measures radiant energy beyond the sensitive range of human eyes. All objects radiate this energy with intensity relative to the temperature of the object. Measurement of infrared radiation is possible due to the flow of net infrared radiation from a hotter to a cooler object.

Infrared radiation also exhibits the same optical behavior associated with light that is visible to the eye such as shadowing, reflection and refraction. Assuming that the instrument is the cooler of the two, the front-end optical telescope collects a sample of infrared radiation from the hotter object. The sample of infrared radiation collected by optics is then focused on the infrared detector. The

infrared detector converts the radiation to an electrical signal, which again is converted to an equivalent digital signal reading the temperature as display numbers in degree Celsius (Fouché and Booysen, 1994).

Figure 3.1 Hand-held infrared thermometer (Series Super Low Cost Infrared Thermometer)

3.2.4.2 Green Seeker hand-held optical sensor unit

Green Seeker is a variable rate application and mapping system designed for on-farm use. Unlike aerial and satellite imagery services, Green Seeker's ground based sensors provide real time data, day or night, regardless of weather conditions. The data can be used to make variable rate applications, map crop health/biomass and vigor, create management zones, identify pest and disease problems, evaluate efficiency of drainage systems, modify soil sampling strategies, monitor and modify irrigation schedules, determine optimum harvesting dates, etc.

The Green Seeker hand held optical sensor unit (figure3.2), is a tool for crop research that provides precision measurement and data logging of the Normalized Difference Vegetation Index (NDVI) and red to near infrared ratios of plant material. The unit can be used to monitor changing field (crop/plant) conditions during the growing season and the effects of different levels of input. The data can later be exported to a desktop computer for analysis.

Figure 3.2 Green Seeker Optical sensor unit.

3.2.4.3 Leaf Porometer

Leaf porometer (figure 3.3) is a lightweight, menu-driven instrument for measuring stomatal conductance. It does this by putting a leaf in series with two known conductance elements, and comparing the humidity measurements between them. Most Leaf porometers have two modes, automatic or manual. The auto mode eliminates subjectivity of measurement by calculating the final conductance based on measurement of conductance over a set period.

Figure 3.3 Lightweight menu-driven Leaf Porometer.

3.2.5 Planting and Watering

Tomato seedlings of two cultivars (*Roma VF* and *Flora Dade*) were transplanted in the pots for the treatment under greenhouse conditions on 06/11/2006 and on 20/09/2007 for the experiment under field conditions. The date for the field treatment was based on the report in (www.growingtomatoe.com) saying tomato seedling transplantation survive well under field conditions from August to October due to moderate climatic conditions, hence they were transplanted on 20/09/2007. The first two weeks after transplantation all the pots were watered every 3 days.

After two weeks watering was done according to the specified treatments; stressed and non-stressed. Stressed plants were watered after every 5 days with an amount of 500ml per pot until 50% flowering stage after that they were watered after every 3 days with the same amount of water until harvest and non-stressed were watered with an amount of 500ml per pot after every 3 days until at 50% flowering stage after that they were watered daily with the same amount until harvest, reported in (www.essortment.com).

3.2.6 Data collection

The following data were collected during the trial:-

- The NDVI values, stomatal conductance and canopy temperature. These data were collected at 50% flowering stage twice daily in the morning (9h00 -11h00) and in the afternoon (12h00-14h00) and also at 50% fruiting stage at the same times (Dusek *et al*., 1985).
- Days taken for 50% flowering and plant height were measured when 50% of the plants had flowered (Lafitte *et al*., 2002).
- Number of fruits per plant (stressed or well-watered) per cultivar (*Roma VF* or *Flora Dade*) was collected. Fruit yield under green house conditions was collected on the 14/01/ 2007(after 69 days transplantation) whereas

under field conditions were collected on the 05/01/2008 (after 106 days of transplantation).

3.2.7 Statistical Analysis

Data collected using NDVI, Infrared thermometer, Leaf Porometer and agronomic traits (plant height, 50% flowering stage, number of fruits per plant and fruit yield per plant) were analysed using the statistical analysis systems (SAS, 2007) and Statistics Package of Social Science (SPSS, 2007). Mean comparisons were carried out using the LSD (least significant difference) test procedure at 5% probability level to assess differences in treatment means.

3.3 Results

3.3.1 Canopy Temperature

Analysis of variance tables for canopy temperature are presented in Appendix 8.1a to 8.1d. The results show stress level, cultivar and stress level* cultivar as sources of variance. At 50% flowering stress level exhibited highly significant interaction with canopy temperature both under greenhouse and field conditions whereas cultivars show highly significant interaction under field condition and no significant interaction under greenhouse conditions, while stress level* cultivar exhibited no significant interaction with canopy temperature under field conditions whereas it shown significant interaction under greenhouse conditions. At 50% fruiting stage stress level, cultivar and stress level*cultivar exhibited highly significant interaction with canopy temperature under both greenhouse and field conditions as indicated in Appendix 8.1 c and 8.1d.

Mean canopy temperature of two tomato varieties under field and green house conditions for stressed and non-stressed treatments measured during morning and afternoon at 50% flowering and at 50% fruiting stage are exhibited in Table 3.4a to 3.4d. Canopy temperature varied with time at which it was recorded, cultivar, environment and stress level. The mean canopy temperature in the morning under field conditions at 50% flowering stage showed a grand mean of 27 ^{o}C for stressed plants and grand mean of 23 ^{o}C for non stressed plants and in the afternoon it showed a grand mean of 36 ^{o}C for stressed plants and 28 ^{o}C for non stressed plants. Roma VF had mean values of 26 ^{o}C for stressed and 22 ^{o}C for non stressed plants in the morning and Flora Dade had mean values of 23 ^{o}C for non stressed plants and 27 ^{o}C for stressed plants (Table 3.4 a).

In the afternoon in the field conditions at 50% flowering stage Roma VF had mean values of 29 ^{o}C for non stressed plants and 36 ^{o}C for stressed plants and Flora Dade had mean values of 27 ^{o}C for non stressed plants and 36 ^{o}C for stressed plants. The mean canopy temperature in the morning under field conditions at 50% fruiting stage showed a grand mean of 27 ^{o}C for stressed plants and a grand mean of 22 ^{o}C for non stressed plants and in the afternoon it showed a grand mean of 33 ^{o}C for stressed plants and 26 ^{o}C for non stressed plants. Under both conditions (greenhouse and field) at 50% flowering and at 50% fruiting stage the coefficient of variance values were very low which indicates the precision of this comparative trial.

Table 3.4a Mean canopy temperature of two tomato varieties under field conditions for stressed and non-stressed treatments measured during morning and afternoon at 50% flowering stage.

	Canopy Temperature (^oC) (Morning)		Canopy Temperature (^oC)(Afternoon)	
	Stressed	**Non- stressed**	**Stressed**	**Non-stressed**
Roma VF	26.00	22.00	36.00	27.00
Flora Dade	27.00	23.00	36.00	29.00
Grand mean	27.00	23.00	36.00	28.00
LSD(0.05)	0.42	0.79	0.67	0.46
C.V.%	1.87	3.95	2.09	1.84
R^2	0.550	0.485	0.916	0.810

Table 3.4b Mean canopy temperature of two tomato varieties under greenhouse conditions for stressed and non-stressed treatments measured during morning and afternoon at 50% flowering stage.

	Canopy Temperature (^oC) (Morning)		Canopy Temperature (^oC)(Afternoon)	
	Stressed	**Non-stressed**	**Stressed**	**Non- stressed**
Roma VF	23.00	20.00	29.00	22.00
Flora Dade	24.00	20.00	29.00	21.00
Grand mean	24.00	20.00	29.00	22.00
LSD(0.05)	0.77	1.19	0.04	0.74
C.V.%	3.68	6.69	7.11	3.91
R^2	0.831	0.406	0.480	0.560

Table 3.4c Mean canopy temperature of two tomato varieties under field conditions for stressed and non-stressed treatments measured during morning and afternoon during 50% fruiting stage.

	Canopy Temperature (^{o}C) (Morning)		Canopy Temperature (^{o}C)(Afternoon)	
	Stressed	**Non-stressed**	**Stressed**	**Non- stressed**
Roma VF	26.00	20.00	29.00	23.00
Flora Dade	27.00	24.00	36.00	28.00
Grand mean	27.00	22.00	33.00	26.00
LSD(0.05)	0.94	0.74	0.67	1.01
C.V.%	2.20	3.78	2.29	4.38
R^2	0.937	0.919	0.981	0.921

Table 3.4d Mean canopy temperature of two tomato varieties under greenhouse conditions for stressed and non-stressed treatments measured during morning and afternoon during 50% fruiting stage.

	Canopy Temperature (^{o}C) (Morning)		Canopy Temperature (^{o}C)(Afternoon)	
	Stressed	**Non-Stressed**	**stressed**	**Non- stressed**
Roma VF	27.00	20.00	28.00	22.00
Flora Dade	23.00	20.00	24.00	21.00
Grand mean	25.00	20.00	26.00	22.00
LSD(0.05)	1.78	0.79	0.06	0.02
C.V.%	5.19	4.43	3.42	3.46
R^2	0.864	0.470	0.940	0.894

3.3.2 NDVI

Analysis of variance (Appendix 8.2a to d) for NDVI between two tomato cultivars, with and without water stress, and two measurement times and their interactions under field and greenhouse conditions at 50% flowering stage showed that stress level exhibited highly significant (P≤ 0.01) interaction for NDVI under field and the greenhouse conditions. Cultivars exhibited highly significant interactions under

field conditions and no significant interactions under greenhouse conditions. Stress level*cultivar showed no significant interactions for NDVI under both field and greenhouse conditions.

At 50% fruiting stress level, cultivar and stress level*cultivar exhibited highly significant interaction for NDVI under both field and greenhouse conditions (Appendix 8.2c and d). The mean NDVI for stressed and non stressed plants under field and greenhouse conditions are showed in Tables 3.5a to 3.5d, NDVI mean differs according to water availability, time, cultivar and environment. The average means for non stressed crops under field conditions at the 50% flowering stage were 0.71 in the morning and 0.55 in the afternoon. For stressed plants the average means were 0.25 in the morning and 0.39 in the afternoon. At 50% fruiting stage average means for stressed plants were found to be 0.53 in the morning and 0.36 in the afternoon and for non stressed plants were 0.73 in the morning and 0.59 in the afternoon.

In the greenhouse average means for non stressed plants at 50% flowering stage were 0.77 in the morning and 0.67 in the afternoon and stressed plants were 0.43 in the morning and 0.42 in the afternoon. At 50% fruiting stage the average means for non stressed plants were 0.79 in the morning and 0.72 in the afternoon and for stressed plants were 0.56 in the morning and 0.43 in the afternoon.

Table 3.5a Mean NDVI of two tomato varieties under field conditions for stressed and non-stressed treatments measured during morning and afternoon at 50% flowering stage.

	NDVI (morning)		**NDVI (Afternoon)**	
	Stressed	**Non-Stressed**	**stressed**	**Non-Stressed**
Roma VF	0.21	0.70	0.35	0.53
Flora Dade	0.28	0.71	0.42	0.56
Grand mean	0.25	0.71	0.39	0.55
LSD(0.05)	0.06	0.05	0.08	0.03
C.V.%	27.85	3.95	22.03	6.79
R^2	0.572	0.508	0.470	0.753

Table 3.5b Mean NDVI of two tomato varieties under greenhouse conditions for stressed and non-stressed treatments measured during morning and afternoon at 50% flowering stage.

	NDVI (Morning)		**NDVI (Afternoon)**	
	Stressed	**Non-stressed**	**Stressed**	**Non-stressed**
Roma VF	0.39	0.78	0.44	0.68
Flora Dade	0.46	0.76	0.40	0.66
Grand mean	0.43	0.77	0.42	0.67
LSD(0.05)	0.08	0.06	0.04	0.04
C.V.%	19.87	8.38	10.95	6.12
R^2	0.537	0.541	0.532	0.696

Table 3.5c Mean NDVI of two tomato varieties under field conditions for stressed and non-stressed treatments measured during morning and afternoon during 50% fruiting stage.

	NDVI (morning)		NDVI (Afternoon)	
	Stressed	**Non-stressed**	**Stressed**	**Non-stressed**
Roma VF	0.53	0.84	0.38	0.63
Flora Dade	0.53	0.62	0.33	0.54
Grand mean	0.53	0.73	0.36	0.59
LSD(0.05)	0.04	0.02	0.08	0.03
C.V.%	19.83	3.01	24.09	5.46
R^2	0.482	0.982	0.514	0.965

Table 3.5d Mean NDVI of two tomato varieties under greenhouse conditions for stressed and non-stressed treatments measured during morning and afternoon during 50% fruiting stage.

	NDVI (Morning)		NDVI (Afternoon)	
	Stressed	**Non- stressed**	**Stressed**	**Non- stressed**
Roma VF	0.53	0.84	0.41	0.79
Flora Dade	0.58	0.74	0.45	0.65
Grand mean	0.56	0.79	0.43	0.72
LSD(0.05)	0.05	0.02	0.06	0.02
C.V.%	9.15	3.28	16.39	3.08
R^2	0.633	0.902	0.532	0.964

3.3.3 Stomatal Conductance

Analysis of variance for stomatal conductance between two tomato cultivars, with and without water stress and two measurement times and their interactions under field and greenhouse conditions at 50% flowering stage showed that stress level exhibited highly significant (P≤ 0.01) interactions with stomatal conductance whereas cultivar exhibited significant interaction under both green- house and

field conditions, stress level*cultivar showed no significant variation under greenhouse conditions but it did showed significant variation under field conditions (Appendix 8.3a and 8.3b).

At 50% fruiting stage analysis of variance for stomatal conductance showed that stress level exhibited highly significant interactions with stomatal conductance under greenhouse and field conditions whereas cultivars exhibited highly significant interactions under field conditions and no significant interactions under greenhouse conditions, stress level*cultivar also exhibited highly significant interactions with stomatal conductance under field conditions and no significant interaction under greenhouse conditions.

Mean stomatal conductance, LSD and C.V at 50% flowering stage and at 50% fruiting stage in the greenhouse and in the field for stressed and non stressed plants are recorded in Tables (3.6a to 3.6d).The average mean values at 50% flowering stage were smaller than after fruiting both in the greenhouse and in the field for non stressed plants in the morning and in the afternoon. Non stressed plants had higher mean average than stressed plants in the greenhouse and in the field as illustrated by Tables (3.6a to 3.6d). For stressed plants under greenhouse and under field conditions at 50%flowering stage in the afternoon average mean values were higher than at 50% fruiting stage (Tables 3.6b to 3.6d).

Table 3.6a Mean stomatal conductance of two tomato varieties under field conditions for stressed and non-stressed treatments measured during morning and afternoon at 50% flowering stage.

	Stomatal conductance(morning) mmol $m^{-2}s^{-1}$		**Stomatal conductance(Afternoon) mmol $m^{-2}s^{-1}$**	
	Stressed	**Non-stressed**	**stressed**	**Non-Stressed**
Roma VF	24.84	173.41	44.38	95.51
Flora Dade	22.11	142.65	43.20	83.58
Grand mean	23.48	158.03	43.79	89.55
LSD(0.05)	7.59	29.77	4.23	6.40
C.V.%	30.01	20.96	10.74	7.96
R^2	0.560	0.721	0.887	0.776

Table 3.6b Mean stomatal conductance of two tomato varieties under green-house conditions for stressed and non-stressed treatments measured during morning and afternoon at 50% flowering stage.

	Stomatal conductance(morning) mmol $m^{-2}s^{-1}$		**Stomatal conductance(Afternoon) mmol $m^{-2}s^{-1}$**	
	Stressed	**Non-stressed**	**Stressed**	**Non-stressed**
Roma VF	74.10	255.40	69.93	249.91
Flora Dade	51.38	207.70	40.88	179.25
Grand mean	62.74	231.55	55.41	214.58
LSD(0.05)	20.49	124.51	31.42	85.83
C.V.%	36.43	59.84	63.11	44.51
R^2	0.665	0.525	0.530	0.656

Table 3.6c Mean stomatal conductance of two tomato varieties under field conditions for stressed and non-stressed treatments measured during morning and afternoon during 50% fruiting stage.

	Stomatal conductance(morning) mmol $m^{-2}s^{-1}$		**Stomatal conductance(Afternoon) mmol $m^{-2}s^{-1}$**	
	Stressed	**Non-stressed**	**Stressed**	**Non-stressed**
Roma VF	55.27	434.28	24.28	302.13
Flora Dade	73.83	294.24	26.25	190.07
Grand mean	73.83	364.26	25.27	246.10
LSD(0.05)	18.64	75.15	11.06	70.99
C.V.%	43.53	22.96	48.71	31.36
R^2	0.666	0.747	0.715	0.379

Table 3.6d Mean stomatal conductance of two tomato varieties under green-house conditions for stressed and non-stressed treatments measured during morning and afternoon during 50% fruiting stage.

	Stomatal conductance (Morning) mmol $m^{-2}s^{-1}$		**NDVI (Afternoon)**	
	Stressed	**Non- stressed**	**Stressed**	**Non- stressed**
Roma VF	55.27	470.40	24.28	313.85
Flora Dade	55.77	434.28	39.44	237.22
Grand mean	55.52	452.39	31.86	275.54
LSD(0.05)	20.43	91.54	14.86	73.16
C.V.%	40.95	22.52	51.90	29.55
R^2	0.688	0.635	0.613	0.617

3.3.4 Plant height

Analysis of variances for plant height showed that stress level exhibited highly significant interactions with plant height under greenhouse and field conditions as well as cultivar whereas stress level*cultivar exhibited no significant interaction with plant height under both greenhouse and field conditions Appendix 8.5 a and 8.5 b.

Table 3.7 shows that the stressed plants were shorter than non stressed plants under both greenhouse and field conditions for both cultivars. Under field conditions average mean for non stressed plants was found to be 34.24 cm and while for stressed plants the average mean 24.35 cm. Under greenhouse condition average mean for non stressed plants was 45.60 cm and for stressed plants was 34.80 cm.

Table 3.7 Mean plant height of two tomato varieties under field and greenhouse conditions for stressed and non-stressed treatments.

	Plant Height (Field) cm		**Plant Height (Greenhouse) cm**	
	Stressed	**Non-stressed**	**Stressed**	**Non-stressed**
Roma VF	22.16	31.37	33.87	43.53
Flora Dade	26.54	37.10	35.72	47.67
Grand mean	24.35	34.24	34.80	45.60
LSD(0.05)	4.96	3.02	5.19	2.17
C.V.%	22.68	9.82	16.59	5.30
R^2	0.515	0.738	0.442	0.758

3.3.5 Days taken for 50% flowering

Analysis of variance for days taken for 50% plants flowering between two tomato cultivars, with and without water stress is represented in Appendix 8.4a and 8.4b. Stress level, cultivar and stress level*cultivar exhibited no significant interaction with days taken for 50% flowering under field and greenhouse conditions.

Mean days taken for 50% flowering of two tomato varieties under greenhouse conditions for stressed and non-stressed plants are recorded in (Table 3.8). Table 3.8 shows that the average men of days taken for 50% flowering for stressed plants under field conditions was 63 days and for non stressed plants was 58 days, while under greenhouse conditions average mean of days taken for 50% flowering was 44 days for stressed and 39 days for non stressed plants.

Table 3.8 Mean days taken for 50% flowering of two tomato varieties under field and greenhouse conditions for stressed and non-stressed treatments.

	Days taken for 50% flowering(Field)		**Days taken for 50% flowering (Greenhouse)**	
	Stressed	**Non- stressed**	**Stressed**	**Non- stressed**
Roma VF	63.00	57.00	42.00	38.00
Flora Dade	63.00	58.00	45.00	40.00
Grand mean	63.00	58.00	44.00	39.00
LSD(0.05)	0.00	0.00	0.00	0.00
C.V.%	0.00	0.00	0.00	0.00
R^2	1.00	1.00	1.00	1.00

3.3.6 Number of fruits per plant

Analysis of variance for number of fruits per plant between two tomato cultivars, with and without water stress under field and greenhouse conditions, is presented in Appendix 8.6a and 8.6b. This shows that stress level exhibited highly significant interactions with number of fruits per plant whereas cultivar and

stress level*cultivar showed no significant interactions with number of fruits per plant, under both greenhouse and field conditions.

Mean performance of number of fruits per plant is recorded in Table 3.9. It shows the average mean values under greenhouse and field conditions for stressed and non stressed plants. None of the means showed significant differences; stressed plants under field conditions having an average mean value of 4.00 and under greenhouse conditions 5.00, while non stressed plants had average mean values of 9.00 under field conditions and 13.00 under greenhouse conditions.

Table 3.9 Mean number of fruits per plant of two tomato varieties for stressed and non-stressed treatments.

	Number of fruits/plant (Field)		**Number of fruits/plant (Greenhouse)**	
	Stressed	**Non-stressed**	**Stressed**	**Non-stressed**
Roma VF	4.00	9.00	5.00	13.00
Flora Dade	4.00	9.00	5.00	13.00
Grand mean	4.00	9.00	5.00	13.00
LSD(0.05)	0.10	1.70	0.54	2.05
C.V.%	30.21	20.67	12.70	17.70
R^2	0.367	0.446	0.464	0.619

3.3.7 Fruit yield per plant

Analysis of variance of fruit yield per plant between two tomato cultivars, with and without water stress, under field and greenhouse conditions, showed that stress level and cultivar as sources of variance having highly significant interactions with fruit yield per plant, whereas stress level*cultivar had no significant interactions with fruits yield per plant under both greenhouse and field conditions (Appendix 8.7a and b).

Mean fruit yield per plant of two tomato varieties under field conditions for stressed and non-stressed treatments is recorded in Table 3.10; no significant variation was shown by the means on non-stressed plants under field conditions and for stressed plants under greenhouse conditions. Average mean values for non stressed plants was 424.44g under greenhouse conditions and 311.32g under field conditions, whereas for stressed plants was 121.19g under greenhouse conditions and 96.75g under field conditions (Table 3.10).

Table 3.10 Mean fruits yield per plant of two tomato varieties for stressed and non-stressed treatments.

	Fruits yield/plant (Field) g		**Fruits yield/plant (Greenhouse) g**	
	Stressed	**Non-stressed**	**Stressed**	**Non-stressed**
Roma VF	104.78	324.66	130.45	452.72
Flora Dade	88.71	297.98	111.93	396.15
Grand mean	96.75	311.32	121.19	424.44
LSD(0.05)	14.55	38.08	19.76	43.05
C.V.%	16.74	13.61	18.14	11.30
R^2	0.711	0.701	0.747	0.864

3.4 Correlation analysis

Correlation coefficients for pair-wise comparison between canopy temperature, NDVI, stomatal conductance, plant height, days taken for 50% flowering, number of fruits per plant, fruit yield per plant with and without moisture stress under field and greenhouse conditions is represented in Tables 3.11 a and 3.11b.

Canopy temperature was found to have a highly significant negative correlation with NDVI, stomatal conductance, plant height, number of fruits per plant and fruit yield, whereas it had a highly significant positive correlation with days taken for 50% flowering. The highly significant negative correlation observed shows

that canopy temperature influenced NDVI, plant height and stomatal conductance negatively hence where canopy temperature is high NDVI and stomatal conductance is low and plant height is restricted because high temperature conditions hardens plant stems and also cause stomata to close and reduce photosynthesis and transpiration (Holmgren *et al.,*1965).

NDVI was found to have a highly significant positive correlation with stomatal conductance, plant height, number of fruits and fruit yield per plant. Highly significant negative correlation was found between NDVI and days taken for 50% flowering (Table3.11a).

A highly significant positive correlation was observed between stomatal conductance and plant height, stomatal conductance and number of fruits and also between stomatal conductance and fruit yield, whereas between stomatal conductance and days taken for 50% flowering highly significant negative correlation was observed. Plant height and days taken for 50% flowering had highly significant negative correlation, but plant height had a highly significant positive correlation with number of fruits per plant and fruit yield. There was a highly significant positive correlation between days taken for 50% flowering and number of fruits per plant as well as days taken for 50% flowering with fruit yield per plant. Number of fruits per plant also had a highly significant positive correlation with fruit yield per plant. The same correlations were observed in both (Tables 3.11a and 3.11b).

3.11a Correlation coefficients for pair-wise comparison between canopy temperature, NDVI, stomatal conductance, plant height, days taken for 50% flowering, number of fruits per plant, fruit yield per plant with and without moisture stress under field conditions.

	CT	**NDVI**	**SC**	**PH**	**DT 50%F**	**NF**	**FY**
CT	1	-0.798**	-0.692**	-0.405**	0.553**	-0.593**	-0.635**
NDVI		1	0.844**	0.657**	-0.841**	0.684**	0.727**
SC			1	0.535**	-0.775**	0.732**	0.777**
PH				1	-0.739**	0.872**	0.844**
50%DTF					1	0.901**	0.759**
NF						1	0.826**
FY							1

** Correlation is significant at the 0.01 level

CT= Canopy temperature, NDVI= Normalized Differential Vegetation Index, PH=Plant height, DT50%F= Days taken for 50% flowering, NF= Number of fruits, FY= Fruit yield

3.11b Correlation coefficients for pair-wise comparison between canopy temperature, NDVI, stomatal conductance, plant height, days taken for 50% flowering, number of fruits per plant, fruit yield per plant with and without moisture stress under greenhouse conditions.

	CT	**NDVI**	**SC**	**PH**	**DT50%F**	**NF**	**FY**
CT	1	-0.710**	-0.467**	-0.580**	0.648**	-0.725**	-0.680**
NDVI		1	0.586**	0.702**	-0.779**	0.802**	0.813**
SC			1	0.539**	-0.662**	0.819**	0.799**
PH				1	-0.580**	0.907**	0.925**
50%DTF					1	0.911**	0.723**
NF						1	0.921**
FY							1

** Correlation is significant at the 0.01 level

CT= Canopy temperature, NDVI= Normalized Differential Vegetation Index, PH=Plant height, DT50% F= days to 50% Flowering, NF= number of fruits, FY= Fruit yield

4. Discussion

The concept of using remote sensing techniques such as an infrared thermometer to measure canopy temperature in order to detect the onset and duration of plant water stress was previously used by many researchers (Tanner, 1963; Wiegand and Namken, 1966; Ehrler and van Bavel, 1967; Astin and van Bavel, 1972; Bartholic *et al.,* 1972; Ehrler, 1973). The findings of this research showed that moisture stress has a major impact on canopy temperature which confirms the work done by Jackson (1982). When plants were exposed to water stressed conditions tend to show high canopy temperatures due to their reduction in transpiration.

The mean values show that stressed plants had higher canopy temperature when compared to non-stressed plants, which confirms the observation made by Jackson (1982), that as plants become water stressed, transpiration will decrease, and thus the leaf temperature will increase (Table 3.4a to 3.4d).

Effective environmental control is necessary for controlled environment plant production systems (CEPPS) to deliver high plant growth rates, yield and quality according to the desired production scheduling. Canopy temperature mean values differ based on environmental conditions. The mean values for canopy temperature were lower under greenhouse conditions than under field conditions (Tables: 3.4a to 3.4d) because the temperature under greenhouse conditions was controlled and kept constant at 28 ^{o}C, but under field conditions temperature was fluctuating and at some times reached 38 ^{o}C, that led to the stressed plants under field conditions having a low transpiration rate which results in higher leaf temperatures than those under greenhouse conditions.

Since the research was conducted from spring to summer, for stressed plants canopy temperature in the afternoon reached 29 ^{o}C and 24 ^{o}C in the morning at 50% flowering stage under greenhouse conditions (Table 3.4c) which indicates that stressed plants were losing a lot of water trying to cool their leaves. Canopy temperatures changed at 50% fruiting stage, for non-stressed plants under greenhouse conditions canopy temperature was found to be 25 ^{o}C in the morning and 26 ^{o}C in the afternoon, as compared to 24 ^{o}C in the morning and 29 ^{o}C in the afternoon at 50% flowering stage. This is because young plants have few stomatal opening hence transpiration is very slow and plants tend to have high canopy temperatures.

The Plant Moisture Stress (PMS) reading at any given time reflects the plant's interaction with the water supply and the demand for water placed upon the plant by its environment. Since this factor is almost always changing, PMS is nearly always changing. The time of measurement therefore requires careful

consideration – PMS is high at midday and low just before sunrise. Pre-sunrise PMS values will usually reflect average soil moisture tension, if the soil is uniformly irrigated. Midday PMS values reflect the tension experienced by the plant as it pulls water from the soil to satisfy the water demand of the atmosphere (www.pmsinstrument.com/important.htm).

The mean value of canopy temperature for Flora Dade and Roma VF for non-stress plants at 50% flowering stage in the morning was the same which was 20 ^{o}C but in the afternoon the mean value of Flora Dade was 21 ^{o}C which was found to be lower than that of Roma VF which was 22 ^{o}C (Table 3.4 b) under greenhouse conditions. Roma VF had lower canopy temperature than Flora Dade for stressed plants in the morning under greenhouse conditions (Table 3.4 b).

At 50% fruiting stage under greenhouse conditions Flora Dade had lower canopy temperature than Roma VF in the afternoon for both stressed and non-stressed plants which shows that greenhouse environment is good condition for Flora Dade plantation.

Under field conditions at 50% flowering stage in the morning stressed plants had an average mean of 27 ^{o}C and in the afternoon they had an average mean of 36 ^{o}C. Harsh temperature conditions caused stressed plants to reduce transpiration hence their canopy temperature was raised to 36 ^{o}C in both cultivars. Roma VF was found to have lower canopy temperature than Flora Dade in the field, at 50% flowering and at 50% fruiting stages, Flora Dade tend to be negatively affected by water stress and change in environmental conditions resulting in very high canopy temperature, hence it reduces its transpiration rate, which leads its canopy temperature to be high (Tables 3.4 a to 3.4d).

A low mean value in both cultivars under well-watered treatments shows that non stressed plants were able to cool better than those which were stressed which confirm the observation made by Jackson (1982) that the plant becomes water

stressed, transpiration will decrease, and thus the leaf temperature will increase. When a leaf is freely transpiring, the cooling properties of the evaporating water keep the leaf temperature below that of the air.

NDVI is the index that uses radiance or reflectance from a red channel around 0.66 μm and a near-IR channel around 0.86 μm. The NDVI values have no units and are one of the variables which were observed in relation to water stress on tomato. NDVI is mostly affected by the anatomical structure of the leaf, leaf age, leaf water content and mineral deficiencies. Near-infrared reflectance is strongly influenced by anatomical structure. It depends on the number of cell layers and relative thickness of the spongy mesophyll.

NDVI values differed in accordance with the time the data was collected, which means time also has an influence on plant greenness because in the morning plants had higher NDVI values than in the afternoon and it was observed under both conditions (stressed and non-stressed). Except under field conditions at 50% flowering stage in the morning stressed plants had an average mean of 0.25 and in the afternoon they had an average mean of 0.39. Low NDVI value under stressed conditions confirms the findings by Glen *et al.* (2004) that NDVI decreases as plant water status decreases.

The high NDVI values indicate healthy leaves and low stress (Botha, 2001). Comparing stress and non-stress plants, stressed plants has a lower NDVI mean values than that of non- stressed plants which indicates that moisture stress has an effect on plant greenness. The difference in NDVI under non-stressed conditions is an indication of physiological characteristics of plants.

The average mean for NDVI increased greatly at 50% fruiting stage as compared to at 50% flowering stage under greenhouse and field conditions. This was caused by leaf maturity in all cultivars because healthy, mature and photosynthetically active leaves will have high absorption in the red spectral band

and high reflection in the near infrared spectral band causing NDVI to be high which supports the finding by Botha (2001) saying that juvenile leaves had lower reflectance than mature leaves. Collins (1978) and Campbell (1996) also said that the internal structure of the leaf is responsible for the bright infrared reflectance of living vegetation.

An average mean value for stressed plants showed that NDVI was affected more negatively under field conditions than under greenhouse conditions. An average mean value for non stressed plants under field conditions at 50% flowering stage was found to be 0.71 in the morning and 0.55 in the afternoon and for stressed plants the average mean was found to be 0.25 in the morning and 0.39 in the afternoon, while under greenhouse conditions at the same stage the average means were found to be 0.77 in the morning and 0.67 for non stressed plants and 0.43 in the morning and 0.42 in the afternoon for stressed plants (Tables 3.5a and 3.5b).

The same trend of plants under greenhouse conditions having high average mean values than plants under field conditions continued even at 50% fruiting stage (Tables 3.5c and 3.5d).

Roma VF at 50% flowering stage was found to have lower mean values on both stressed and non stressed plants under field conditions as compared to Flora-Dade (table 3.5a). Under greenhouse conditions at 50% flowering and at 50% fruiting stages for non-stressed plants Roma VF was found to have higher mean values as compared to Flora-Dade (Tables 3.5b and 3.5d).

High leaf porosity values indicate healthy leaves because stressed plants close their stomata to avoid water loss during transpiration hence their porosity value decreases. High leaf porosity increases CO_2 diffusion into the leaf and favors higher photosynthetic rates (Lu, *et al.,* 1998). Higher photosynthetic rates could in turn favor a higher biomass and higher crop yields.

In the afternoon the leaf porosity of both cultivars decreased in stressed and non-stressed plants under greenhouse and field conditions. This is due to the fact that when the sun is bright (which is when evaporation is greatest) plants close their stomata in order to reduce evaporation speed. However, the speed of photosynthesis depends on being able to release the O_2 produced into the atmosphere, so closing the stomata too much or for too long reduces photosynthate. Therefore, plants keep opening and closing their stomata to keep a middle line between the two constraints (www.gardenwithinsight.com).

In the vegetative stage of growth, the amount of water usage is directly proportional to the transpiration and thus dry matter production. The more rapid the leaf area development (i.e. leaf expansion), the greater the transpiration rate and the faster the use of available water. Once the canopy is full, transpiration will be determined mainly by the conductance of water through the stomata and once they have closed, through the cuticle of the leaf. When stomata are open, both photosynthesis and transpiration is high (Fischer and Fukai, 2003).

According to Parson and Wheaton (1995) water stress is one of the major factors that promote stomatal closure. When the leaf matures it tends to have many stomatal openings which make it transpire more than young leaves which have few and under developed stomata and that cause plants at 50% fruiting stage to have higher stomatal conductance mean values than at 50% flowering stage.

Roma VF was found to have higher stomatal conductance values under green-house and under field conditions at 50% flowering stage for both stressed and non stressed plants than Flora-Dade. At 50% fruiting stage under greenhouse and field conditions Flora-Dade had higher stomatal conductance for stressed plants as compared to Roma VF (Tables 3.6 c and 3.6d).

The mean value for stomatal conductance of Roma VF in the morning for non stressed plants under greenhouse conditions was 255.40 mmol $m^{-2}s^{-1}$as compared to 173.41 mmol $m^{-2}s^{-1}$ under field conditions at 50% flowering stage, and in the afternoon was 249.91 mmol $m^{-2}s^{-1}$ for non stressed plants under greenhouse conditions as compared to 95.51 mmol $m^{-2}s^{-1}$ under field conditions, showing a huge difference in stomatal conductance due to different environmental conditions (Table 3.6a and 3.6b). The huge difference in the mean values based on environmental conditions shows that Roma VF closed its stomatal pores under field conditions as compared to under greenhouse conditions in order to reduce evaporation speed.

In the afternoon under both greenhouse and field conditions stomatal conductance tends to be low for stressed and non stressed plants and the canopy temperature in both stressed and non stressed plants was found to be high. This conforms to the findings of Holmgren *et al.* (1965) who stated that leaf temperature has an influence on stomatal conductance. As the temperature decreases stomatal conductance decreases.

The mean plant height for Flora Dade was more than that of Roma VF (Table 3.7) showing that Flora Dade plants were taller than those of Roma VF under stressed and non-stressed conditions, the difference in the mean values under non-stressed conditions having been caused by physiological characteristics of the cultivars since they were exposed to the same climatic conditions and they were given equal amounts of water and fertilizers. Stem elongation and flowering days were delayed in both cultivars under stressed conditions which confirm observations made by Wilson and Ng (1975). NDVI and stomatal conductance played no role in plant height and days to flowering, unlike canopy temperature.

Moisture stress has an influence on plant height and days taken for 50% flowering. According to Fischer *et al.* (2003) water stress delays flowering days and reduces flower development by 30% which will eventually influence plant yield. Plant height is mostly affected by water stress as is indicated in (Table 3.8). According to Relf *et al*. (2004) if the tomato plant does not receive enough moisture and/or available nitrogen, these can hinder growth and flower production.

Table 3.8 shows that Roma VF takes fewer days to flower than Flora Dade. Under greenhouse conditions Roma VF stressed plants took 42 days for 50% of plants to flower while Flora Dade took 45 days, whereas Roma VF non stressed plants took 38 days and Flora Dade took 40 days. Under field conditions for stressed plants both Roma VF and Flora Dade took equal days for 50% of plants to flower while for non stressed plants Roma VF took 57 days and Flora Dade took 58 days.

Plants under field conditions tend to take more days to flower than plants under greenhouse conditions. Under greenhouse conditions it took an average of 39 days for 50% of plants to flower under non stressed conditions as compared to 58 days under field conditions. It took stressed plants 44 days for 50% plants to flower under greenhouse conditions and 63 days under field conditions.

Due to harsh temperature conditions which at times went very high and then changed to be low, flowering decreased in both cultivars under field conditions for water stressed plants as well as for non-stressed plants, which confirms the findings report in hppt//:nutsidea.net/jotter/tomatoplanting that indicates failure of tomato flowers to set occurs when temperatures are lower than 5 ^{o}C or higher than 35 ^{o}C because of the stem hardening caused by extremely harsh conditions.

When plants were water stressed, they tend to produce less fruits per plant as compared to when they were not stressed (Table 3.9). On average both plants had 13.00 fruits per plant for non-stressed as compared to stressed plants which had only 5.00 fruits per plant under greenhouse conditions indicating that water stress can reduce plant yield by more than 50% both according to the findings of this experiment and also the findings of Parson and Wheaton (1995).

Low temperatures reduce the production and viability of pollen. High temperature, especially if accompanied by low humidity and moisture, hinders tomato fruit set through failure in pollination and/or fertilization, while low night temperatures reduce tomato fruiting (Relf *et al.,* 2004). Abdalla and Vererk (1968) showed that hot temperatures in excess of 30°C adversely affect fruit set for certain cultivars. El Ahmadi (1977) demonstrated that even a thermo cycle of 26/20°C could interrupt fruit set, a short-term exposure of 35°C severely inhibit fruit formation. In our experiment canopy temperature for stressed plants in the field reached 36°C which caused stressed plants to produce 4.00 fruits per plant as compared to 9.00 per plant produced by non stressed plants.

Controlled environmental conditions were good for tomato growth and fruit yield, the plants under greenhouse conditions producing more fruits as compared to plants under field conditions, for both stressed and non stressed plants. Non-stressed plants under greenhouse conditions produced 13.00 fruits per plant and under field conditions produced 9.00 fruits per plant. Factors that caused plants under field conditions to produce less fruits are storms which cause flowers to fall, heavy rains and high temperatures since under field conditions such factors were not controlled as compared to greenhouse conditions.

According to Pyke (1981) fruit set per branch tends to increase with increases in both the number of flowers per branch and branch height. Due to harsh environmental conditions under field conditions which resulted in poor flower forming, plants under field conditions produced less fruit than plants under greenhouse conditions.

Moisture has a big impact on fruit production. Hence fruits produced by stressed plants are few as compared to non-stressed plants. Well watered plants produce bigger and fresher fruits than stressed plants which in turn affects the weight of fruits per plant. According to a report in (www.growingtomatoe.com) 60% of tomato fruit is made up of water so if plants are not supplied with enough moisture they become small and less weight.

Cultivar also played an important role in yield per plant. Fruit yield per plant differed due to cultivar. Although each cultivar had an average of 4.00 fruits per plant under field conditions for stressed plants, Roma VF was found to have a higher a yield of 104.78 g per plant than Flora Dade with a yield of 88.71 g per plant. Under greenhouse conditions Roma VF had a yield of 452.72 g per plant for non-stressed plants whereas Flora Dade had a yield of 396.15 g per plant. Higher yield per plant in Roma VF indicates that Roma VF produced bigger fruits than Flora Dade since both cultivars produced the same number of fruits per plant (Table 3.10). This finding contradicts the observation reported in (www.growingtomatoe.com) which indicates that Flora Dade produces bigger, fleshier and healthier fruits when well watered than Roma VF.

5. Conclusion

The aim of this experiment was to evaluate the effect of moisture stress, using non-destructive remote sensing techniques and agronomic traits (plant height, days taken for 50% flowering, fruit yield per plant and number of fruits per plant) on tomato under field and greenhouse conditions.

- Infrared thermometer which is one of remote sensing techniques, demonstrated clearly that as plants became stressed their canopy temperature increased due to reduction in transpiration.
- Green Seeker NDVI sensor- proved to be an effective tool in determining water stress in tomato. The findings of the research showed that moisture stressed plants had lower NDVI values as compared to non-stressed plants, NDVI decreasing as plant water status decreases.
- Leaf porometer- which measures stomatal conductance proved to be a suitable tool in evaluating moisture stress in plants. Water stressed plants had lower stomatal conductance values as compared to non-stressed plants.
- Days taken for 50% flowering - when plants were under water stress they took more days to flower than non-stressed plants.
- Plant height- stressed plants were shorter compared to non-stressed plants under greenhouse and field conditions.
- Number of fruits per plant- stressed plants produced fewer fruits than non-stressed plants.
- Yield per plant- stressed plants have lower fruit yield per plant as compared to non- stressed plants.

From the findings of this research one can conclude that non-destructive and inexpensive remote sensing techniques, as well as agronomic traits, could be effective tools in monitoring moisture stress in tomato.

6. Future research and Recommendations

The results of the study indicate that the use of remote sensing techniques such as Green Seeker NDVI optical sensor and infrared thermometer as well as leaf porometer and agronomic traits can be an effective and inexpensive technique for evaluating the effect of moisture stress on tomato. It is recommended that since the research was done using only two tomato cultivars, it should be conducted for other cultivars using the same methodology in order to assist in developing a successful, water saving irrigation model for tomato.

7. References

ABDALLA, A. A. & VERKERK, K., 1968. Growth, flowering and fruit-set of the tomato at high temperature. Neth. J. Agric. Sci., 16:71-76.

ASRAR, G., FUCHS, M., KANEMASU, E. T. & HATFIELD, J. L., 1984. Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat, Agron.1. 76:300-306.

ASTON, A. R. & VAN BAVEL, C. H. M., 1972. Soil Surface Water Depletion and Leaf temperature. Agron .J. 64:368-373.

AULAKH, M.S., DORAN, J.M. & MOSIER, A.R., 1992. Soil denitrification-Significance, measurement, and effects of management. *Advances in Soil Science* 18: 1-57. (See page 12).

BARNARD, R.O., BUYS, A.J., COETZEE, J.G.K., DU PREEZ, C.C., MEYER, J.H., VAN DER MERWE, A.J., VAN VUUREN, J.A.J. & VOLCHENK, J .E., 1990. Handbook of standard soil testing methods for Advisory purposes. Soil Science Society of South Africa. Pretoria.

BARTHOLIC, J. F., NAMKEN, L. N., & WIEGAND, C. L., 1972. Aerial thermal scanner to determine temperatures of soils and of crop canopies differing in water *stress, Agron. I.*64:603-608.

BAUDER, 2003. How and When Does Water Stress Impact Plant Growth and Development. Montana State University-Bozeman waterquality.montana.edu/docs/irrigation/a9_bauder.shtml. Accessed: [24/06/2008].

BOTHA, E.J., 2001. Estimating Nitrogen status of crops using Non-destructive Remote Sensing Techniques.M.Sc Thesis. University of the North. South Africa. Page 5-15 and 52-65

BOWMAN, W.D., 1989. The relationship between leaf water statuses, gas exchange and spectral reflectance in cotton leaves. Remote Sensing of Environment 30, 249-255.

BRIX, H., 1979. Effects of plant water stress on photosynthesis and survival of four conifers. Can., J. Forest Res. 9. 160 -5.

BRYANT, R.B. & MORAN, M.S., 1999. Determining crop water stress from crop canopy temperature variability. In: Proceedings of the ‘‘international airborne remote sensing conference’’, Ottawa, Ontario, Canada, 21–24 June 1999, pp I289-I296.

BUYS , A.J., 1991. Bemestingshandleiding, 5th ed. FSSA. Hennopsmeer.

CAI, H. J. & KANG, S. Z., 1997. The changing pattern of cotton crop canopy temperature and its application in detecting crop water stress. *Irrigation & Drainage*, 16(1): 1-5. (in Chinese).

CAMPBELL, J.B., 1996. Introduction to Remote Sensing. Taylor and Francis. London.

CAMPBELL, G.S. & DIAZ, R. 1988. Simplified soil water balance model to predict crop transpiration. In: *Drought Research Priorities for Dryland Tropics.* (F.R. Bidinger and C. Johanson). Pp. 15-26.

CARLSON, R.E., YARGER, D.N. & SHAW, R.H., 1971. Factors affecting the spectral properties of leaves with special emphasis on leaf water status. Agronomy Journal 63, 486-489.

CLAWSON, K. L. & BLAD, B. L., 1982. Scheduling corn irrigation by utilizing infrared thermometry. Agron J. 74:311-316.

COLLINS, W., 1978. Remote Sensing of crop type and maturity. *Photogrammetric Engineering and Remote Sensing*. 44(1): 43-55.

CURCIO, J. A. & PETTY, C.C., 1951. The near infrared absorption spectrum of liquid water. *Opt. Soc. Am*. 41: 302-304.

DOORENBOS, J. & PRUITT, W.O., 1977. Crop water requirements. *FAO Irrigation and Drainage Paper* 24. FAO, Rome.

DRISSEN, P.M. 1986. The water balance of soil. Modelling of Agricultural Production: Weather. Soils and Crops. PUDOC. Wageningen. The Netherlands. Pp. 76-116.

DUSEK, D.A., JACKSON, R. D. & MUSICK, J.T., 1985. Winter wheat vegetation Indices calculated from combinations of seven spectral bands. *Remote sens. Environ. 33: 55-64.*

DREYER, L., 1990. An investigation to determine the potential of digital Landsat Thermic mapper data in determination of vegetation condition classes in natural systems. MSc. Thesis, University of Potchefstroom, South Africa.

EHRLER, W. L. & VAN BAVEL, C. H. M., 1967. Sorghum foliage response to changes in soil water content. Agron. J., 59:404-409.

EHRLER W. L., 1973. Cotton leaf temperatures as related to soil water depletion and meteorological factors, Agronomy Journal, 65, 404-409.

EL AHMADI, A.B., 1977. Genetics and physiology of high temperature tolerance in tomato. PhD Disseration., The Ohio State University, Columbus, OH.

ESCOBAR, D.E., EVERITT, J.H. & DAVIS, M.L., 1988. Potential of mid Infrared video imagery for use in irrigation management studies. Proc. First workshop on videography. ASPRS., Falls church, Virginia, Pp 248- 255.

EVERITT, J.H. & NIXON, J. R., 1986. Canopy reflectance of two droughts-Stressed shrubs, *Photogramm*. Eng. *Remote Sens*. 52: 1189-1192.

EVERITT, J. H., ESCOBAR, D. E., ALANTZ, M. A. & DAVIES, M.R., 1987. Using airborne mid-infrared video imagery for distinguishing plant species and soil conditions. Remote sens. Environ, 22: 423 – 428.

FEYRER, J.R., 1986. Tomato plant `Pezzulla`. Document Type and Number: United States Patent PP05812 [Accessed: 15/05/2008].

FISCHER, K.S., LAFITTE, R., FUKAI, S. & HARDY, B., 2003. Breeding Rice for drought – prone environments. Los Banos (Philippines): IRRI. Pp 98.

FOUCHÉ, P.S., 1993. Estimation of crop water stress on short term crops using low altitude aerial infrared thermometry and colour infrared photography. Proc. 14 th Biennial workshop on colour aerial photography and videography in plant Sciences. ASPRS., (in press).

FOUCHÉ, P.S. & BOOYSEN, N.W., 1994. Assessment of Crop Stress Conditions Using Low Altitude Aerial Color-infrared Photography and Computer Image Processing. *Geocarto international*.9 (2): 25-31.

FUCHS, M., 1990. Infrared measurement of canopy temperature and detection of plant water stress. Theor. Appl. Climatol. , 41: 253- 261.

GARDNER, B. R., BLAD, B. L., GARRITY, D. P. & WATTS, D. G., 1981. Relationships between crop temperature, grain yield, evaporation and phenological development in two hybrids of moisture stressed sorghum. Irr. Sc., 2: 213-224.

GARRITY, D. & O'TOOLE, J. C., 1995. Selection for reproductive stage drought Avoidance of rice by infrared thermometer. Agron. J. 87: 773 – 779.

GATES, D. M., 1980. Biophysical Ecology, Springer-Verlag, New York, Heidelburg, Berlin.

GAUSMANN, H.W, ALLEN, W.A, ESCOBAR, D.E, RICHARDSON, A.J & CARDENAS, R., 1971. Age effects of cotton leaves on light reflectance, transmittance, and absorption and on water content and thickness. Agronomy Journal 43, 465-469.

GEISER, K. M., SLACK, D.C, ALLRED, E.R. & STRANGE., 1982. Irrigation using crop canopy minus air temperature differences.Trans. Asae, 22: 309-322.

GLEN, L. R., GRAIG, W. B., WHITAKER, J. & MILLS, C., 2004. Cotton irrigation timing using Remote Sensing. Crop and Soil Science, University of Georgia, Tifton.

GONZA´ LEZ-DUGO, M.P., BRYANT, R. B. & MORAN, M.S., 2000. Uso de la variabilidad te´ rmica en la determinacio´ n del estre´s hı´ drico en cultivos. In: Proceedings of ''XVIII Congreso Nacional de Riegos'', Huelva, Spain, 20–22 June 2000 (in Spanish).

GRAEFF, S., STEFFENS, D. & SCHUBERT, S., 2001. Use of reflectance measurements for the early detection of N, P, Mg, and Fe Deficiencies in *Zea mays* L. Journal of Plant Nutrition and Soil Science 164, 445-450.

GRANT, L., 1987. Diffuse and specular characteristics of leaf reflectance. Remote Sens. Environ. , 22: 309 – 322.

GUOLIANG , T., 1989. Spectral signatures and vegetation indices of crops. Division Report 89/4. CSIRO, Australia.

GUYOT, G., 1990. Optical properties of vegetation canopies. *In: Steven, M.D* and Clark.J.A. Applications of Remote Sensing in Agriculture. Butterworths. London.

HOLMGREN, P., JARVIS, P.G. & JARVIS, M.S., 1965. Resistances to carbon dioxide and water vapour transfer in leaves of different plant species. Physiologia Plantarum 18:557-573.

HOPE, A. S., 1988. Estimation of wheat canopy resistance using combined remotely sensed spectral reflectance and thermal *observations, Remote Sens. Environ.* 24:369-383.

HORLER, D. N. H. & BARBER., 1981. Principles of remote sensing of plants – in plants and the daylight spectrum. (H. Smith, Ed.) Academic Press, New York.

HOWELL, T.A., HATFIELD, J.L., YAMADA, H. & DAVIES, K.R., 1984. Evaluation of cotton canopy temperature to detect crop water stress, trans. ASAE. , 27: 84 - 88.

HUNT E.R (Jr), ROCK, B.N. & NOBEL, R.S., 1987. Measurement of leaf relative water content by infrared reflectance. Remote Sensing of Environment 22.

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

JACKSON, R. D., REGINATO, R.J. & IDSO, S.B., 1977. Wheat canopy temperature: A practical tool for evaluating water requirements. Water Resource Res., 13: 651-656.

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

JACKSON, R.D., 1982. Canopy temperature and crop water stress. In: *Advances in Irrigation.* Hillel, D. (Ed.). 1: 43-85. Academic Press, New York.

JACKSON, R.D, SLATER, P.N. & PINTER, P.J., 1983. Discrimination of growth and water stress in wheat by various vegetation indices through clear and turbid atmospheres. Remote Sensing of the Environment 15, 187-208.

JACKSON, R. D., & EZRA, C. E., 1985. Spectral response of cotton to suddenly induced water stress, *Int. I. Remote* Sens. 6:177-185.

JACKSON, R.D., 1986. Remote sensing of biotic and abiotic plant stress. Ann. Rev. Phytopathol, 24: 265 – 287.

JACQUEMOND, S. & BARET, F., 1990. PROSPECT: A model of leaf optical Properties spectra. *Remote Sensing. Environ*. 34:75-91.

KANEMASU, H.D., 1985. Plant leaf optical properties in visible and near- infrared light. Graduate studies, No.29, Texas Tech. University USA.

KANEMASU, E.T., DEMETRIADES-SHAH, T.H. & LANG, A.R.G., 1990. Estimating Grassland biomass using remotely sensed data. In: steven, M.D And Clark, J. A. Application of remote sensing in agriculture. Butterworth. London.

KEATINGE, J.D.H. & COOPER, P.J. M. 1984. Physiological and moisture use studies on growth and development of winter sown chickpea. Pages 141-177 in Ascochyta blight and winter sowing of chickpeas. World crops: production, utilization, description Volume 9, (Saxena, MC and Singh, KB eds.) The Hague, Netherlands.

KUMAR, J. & MONTEITH, J.L., 1982. Remote Sensing of crop growth. In Plants and the Daylight Spectrum, edited by H Smith (London Academic Press). Pp 133-144.

LAFITTE, R., BLUM, A., & ATLIN, G., 2002. Using secondary traits to help Identify drought-tolerant genotypes. IRRI. Philippines, Israel.

LEAMER, R.W., NORIEGA, J.R. & WIEGAND, C.L., 1978. Seasonal changes in Reflectance of two wheat cultivars. *Agron. J*. 20:113-118.

LEBOEUF, J., 2006. Effects of Dry Conditions on the Tomato Plant. OMAFRA. http://www.omafra.gov.on.ca/english/crops/facts/dry-tomato.htm [Accessed: 12/06/2008].

LEPORT, L., TURNER, N.C., FRENCH, R.J., BARR, M.D., DUDA, R., DAVIES, S.L., TENNANT, D. & SIDDIQUE., K.H.M., 1999. Physiological responses of chickpea genotypes to terminal drought in a Mediterranean-type environment. European Journal of Agronomy 11, 279-291.

LU, Z. M., PERCY, R. G., QUALSET, C. O. & ZEIGER, E., 1998. Stomatal conductance predicts yields in irrigated Pima cotton and bread wheat grown at high temperatures. *J. Exp. Bot*. 49: 453–460.

MAAS, S. J., 1998. Estimating cotton canopy ground cover from remotely sensed scene reflectance. Agron. J. 90:384-388.

MACVICAR, C.N., 1991.Soil classification: a taxonomic system for South Africa. Department of Agricultural Development. Pretoria.

MORAN, M.S., PINTER, P.J (JR)., CLOTHIER, B.E. & ALLEN, S.G., 1989. Effect of water stress on the canopy architecture and spectral indices of irrigated Alfalfa. Remote sensing of environment, 29, 251-261.

NEMANI, R. R., & RUNNING, S. W.,1989. Estimation of regional Surface resistance to evapotranspiration from NDVI and thermal-IR AVHRR data, *1 Appl. Meteorol.* 28:276-284.Nobel, P. S. (1983), *Biophysical.*

NIELSEN, P. 1990. Non-water stressed baselines for sunflowers. Agric. Water Manage. 26: 265-276.

NILSON, H.E., 1995. Remote Sensing and Image analysis in plant pathology. Annu. Rev. *Phytopathol*. 15: 489-527.

OBREZA, T.A., PITTS, D. J., MCGOVERN, R. J., & SPREEN, T. H., 2001. Deficit Irrigation of Micro-Irrigated Tomato Affects Yield, Fruit Quality, and Disease Severity. Florida Agric. Exp. Stn. Journal Series No. R - 04626.

OSBORNE,S.L., SCHEPERS, J.S., FRANCIS, D.D. & SCHLEMMER, M.R., 2002. Detection of phosphorous and nitrogen deficiencies in corn using spectral radiance measurements. Agronomy Journal 94, 1215-1221.

PARSON, L. & WHEATON, T. A., 1995. Citrus Irrigation: Why Is It Important To You. Article: Citrus Industry Magazine [Accessed: 20/05/2008].

PENUELAS, J, FILELLA, I, BIEL, C, SERRANO, L. & SAVÉ, R., 1993. The reflectance at the 950-970 nm regions as an indicator of plant water stress. International Journal Remote Sensing 14, 1887-1905.

PLANT, R.E., MUNKS, D.S., ROBERTS, B.R., VARGAS, R.L., RAINS, D.W. TRAVIS, R.L., & HUTMACHER, R.B., 2000. Relationships between Remotely Sensed reflectance data and cotton growth and yield. Transactions of the ASAE. 43:535-546.

PYKE, G. H., 1981. Effects of inflorescence height and number of flowers per inflorescence on fruit set in waratahs (*Telopea speciosissima*). *Australian Journal of Botany* 29(4) 419 – 424.

RAHMAN, S. M. L.; NAWATA, E. & SAKURATANI, T., 1998. Effect of water stress on physiological and morphological characters among tomato (Lycopersicon esculentum Mill.) cultivars.

RATLIFF, L. F., RITCHIE, J. T. & CASSEL, D. K., 1983. Field-measured limits of soil water availability as related to laboratory-measured properties. Soil Sci. Soc. Am. J. v47. 770.

RELF, D., MCDANIEL, A. & MORSE, R., 2004."*Tomatoes*", Virginia Cooperative Extension, Virginia Tech.

RICHARDSON, A. J., & EVERITT, J. H., 1987. Monitoring water stress in buffelgrass using hand-held radiometers, *Int. 1. Remote Sens.* 8:1797-1806.

RIPPLE, W. P.,1986. Spectral reflectance relationships to leaf water stress, *Photogramm. Eng. Remote Sens.* 52:1669-1675.

RYLSKI, I., 1979. Fruit set and development of seeded and seedless tomato fruits under diverse regimes of temperature and pollination. J. Amer. Soc. Hort. Sci. 104(6): 835-838.

SAS INSTITUTE INC., 2007. *Version 8,* Cary. Northern Carolina. USA.

SAWHNEY, V.K. & POLOWICK, P.L., 1985. Fruit development in tomato: the role of temperature. Can. J. Bot. 63: 1031-1034.

SHELDRAKE, A.R. & SAXENA, N.P., 1979.Growth and development of chickpeas under progressive moisture stress. Pages 463-483 in Stress physiology of crop plants (Mussell, H and Staples, RC eds.) New York, USA: Wiley.

SLACK, D. C., GEISER, K. M., STRANGE, K. W. & ALLRED, E. R., 1981. Irrigation scheduling in sub humid regions with infrared thermometry. In: Irrigation Scheduling for Water and Energy Conservation in the 80's. Proc. of ASAE Irrig. Scheduling Conf., Dec. 1981, Am. Soc. Agric. Eng. St. Joseph, MI, Pp. 116-124.

SMITH, R.C.G., BARRS, H.D., STEINER, J. L. & STAPPER, M., 1985. Relationship between wheat yield and foliage temperature: theory and its application to infrared measurements. Agric. and Forest. Meteo. 36: 129-143.

SPSS INC., 2007. Headquarters, 233 S. Wacker Drive, Chicago, Illinois 60606

STOCKLE, C.O. & DUGAS, W. A., 1992. Evaluating canopy temperature based indices for irrigation scheduling. Irrig. Sci. 13, 31-37.

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

TARPLEY, L.R, SASSENRA, T.H, K.R. & COLE, G.F., 2000. Reflectance indices with precision and accuracy in predicting cotton leaf nitrogen concentration. Crop Science. 40, 1814-1819.

THOMPSON, D. R., & WEHMANEN, O. A., 1979. Using Landsat digital data to detect moisture stress, *Photogramm. Eng. Remote Sens.* 45:201-207.

TUCKER, C. J., 1980. Remote sensing of leaf water content in the near infrared, *Remote Sens. Environ.* 10:23-32.

TUCKER, C. J., & SELLER, P. J., 1986. Satellite remote sensing of primary production, *Int. Remote Sens.* 7:1395-1416.

TUCKER, C.J., 1979. Red and Photographic infrared linear combination for monitoring vegetation. Remote Sensing of Environment. 8:127-150.

WALSH, S. J., 1987. Comparison of NOAA AVHRR data to meteorologic drought indices, *Photogramm. Eng. Remote Sens.* 53:1069-1074.

WIEGAND, C. L. & NAMKEN, L. N., 1966. Influence of plant moisture stress, solar radiation, and air temperature on cotton leaf temperatures. Agron. J., 58:582-586.

WIEGAND, C. L., GAUSMAN, H. W. & ALLEN, W. A., 1972. Physiological factors and optical parameters as bases of vegetation discrimination and stress analysis, in *Proceeding of the Seminar on Operational Remote Sensing,* American Society of Photogrammetry, Falls Church, VA, pp. 82-102.

WILSON, J.R. & NG, T.T., 1975. Influence of water stress on parameters associated with herbage quality of *Panicum maximum* var. *trichoglume. Australian Journal of Agricultural Research* 26(1) 127 - 136.

WRAITH, J. M. & BAKER, J. M., 1991. High-Resolution Measurement of Root Water uptake using automated time-domain reflectometry. Soil Sci Soc Am J 55:928-932.

http//.ms.essortment.com: [Accessed: 20/10/2007]

http://www.backyardgardener.com [Accessed: 08/01/2007]

www.gardenwithinsight.com [Accessed: 15/04/2008]

www.growingtomatoe.com: [Accessed: 12/02/ 2008]

http//. nutsidea.net/jotter/tomatoplanting: [Accessed: 23/06/2008]

www.pmsinstrument.com/importan.htm: [Accessed: 23/06/2008]

8. APPENDIX

1. Analysis

Appendix 8.1a Analysis of variance for canopy temperature between two tomato cultivars, with and without water stress and their interactions under field condition at 50% flowering stage.

Sources of variations	SS	DF	MS	F	Fprob
SL	737.042	1	737.042	1628.276	0.000**
Cul	9.375	1	9.375	20.711	0.000**
SLx Cul	1.042	1	1.042	2.301	0.133ns
Error	39.833	88	0.453		
Total	76030.000	96			

R Squared = 0.984
** Significantly different at P=0.01
SL= Stress level, Cul= cultivar

Appendix 8.1b Analysis of variance for canopy temperature between two tomato cultivars, with and without water stress and their interactions under green house condition at 50% flowering stage.

Sources of variations	SS	DF	MS	F	Fprob
SL	726.000	1	726.000	360.271	0.000**
Cul	0.375	1	0.375	0.186	0.667ns
SLx Cul	9.375	1	9.375	4.652	0.034*
Error	177.333	88	2.015		
Total	53016.000	96			

R Squared = 0.864
** Significantly different at P=0.01
* Significantly different at P=0.05
SL= Stress level, Cul= cultivar

Appendix 8.1c Analysis of variance for canopy temperature between two tomato cultivars, with and without water stress and their interactions under field condition at 50% fruiting stage.

Sources of variations	SS	DF	MS	F	Fprob
SL	840.167	1	840.167	922.262	0.000**
Cul	330.042	1	330.042	362.291	0.000**
SLx Cul	8.167	1	8.167	8.965	0.004**
Error	80.167	88	0 .911		
Total	2070.958	96			

R Squared = 0.961
** Significantly different at P=0.01
SL= Stress level, Cul= cultivar

Appendix 8.1d Analysis of variance for canopy temperature between two tomato cultivars, with and without water stress and their interactions under green house condition at 50% fruiting stage.

Sources of variations	SS	DF	MS	F	Fprob
SL	610.042	1	610.042	627.879	0.000**
Cul	216.000	1	216.000	222.316	0.000**
SLx Cul	51.042	1	51.042	52.534	0.000**
Error	85.500	88	0 .972		
Total	53512.000	96			

R Squared = 0.919
** Significantly different at P=0.01
SL= Stress level, Cul= cultivar

Appendix 8.2a Analysis of variance for NDVI between two tomato cultivars, with and without water stress and their interactions under field condition at 50% flowering stage.

Sources of variations	SS	DF	MS	F	Fprob
SL	2.297	1	2.297	638.103	0.000**
Cul	0.052	1	0.052	14.390	0.000**
SLx Cul	0.012	1	0.012	3.313	0.072ns
Error	0.317	88	0.004		
Total	24.209	96			

R Squared =0 .902
** Significantly different at P=0.01
SL= Stress level, Cul= cultivar

Appendix 8.2b Analysis of variance for NDVI between two tomato cultivars, with and without water stress and their interactions under green house condition at 50% flowering stage.

Sources of variations	SS	DF	MS	F	Fprob
SL	726.000	1	726.000	360.271	0.000**
Cul	0.000	1	0.000	0.068	0.794ns
SLx Cul	0.008	1	0.008	2.065	0.154ns
Error	0.344	88	0.004		
Total	33.886	96			

R Squared = .868
** Significantly different at P=0.01
SL= Stress level, Cul= cultivar

Appendix 8.2c Analysis of variance for NDVI between two tomato cultivars, with and without water stress and their interactions under field condition at 50% fruiting stage.

Sources of variations	SS	DF	MS	F	Fprob
SL	1.463	1	1.463	922.262	0.000**
Cul	0.450	1	0.450	177.097	0.000**
SLx Cul	0.241	1	0.241	94.923	0.000**
Error	0.223	88	0 .911		
Total	2.759	96			

R Squared = 0.961
** Significantly different at P=0.01
SL= Stress level, Cul= cultivar

Appendix 8.2d Analysis of variance for NDVI between two tomato cultivars, with and without water stress and their interactions under green house condition at 50% fruiting stage.

Sources of variations	SS	DF	MS	F	Fprob
SL	1.662	1	1.662	723.135	0.000**
Cul	0.039	1	0.039	16.886	0.000**
SLx Cul	0.169	1	0.169	73.625	0.000**
Error	0.202	88	0 .002		
Total	39.589	96			

R Squared =0.913
** Significantly different at P=0.01
SL= Stress level, Cul= cultivar

Appendix 8.3a Analysis of variance stomatal conductance between two tomato cultivars, with and without water stress their interactions under field condition at 50% flowering stage.

Sources of variations	SS	DF	MS	F	Fprob
SL	195057.555	1	195057.555	398.806	0.000**
Cul	3258.505	1	3258.505	6.662	0.012*
SLx Cul	2255.251	1	2255.251	4.611	0.035*
Error	43041.146	88	489.104		
Total	900658.370	96			

R Squared =0.859
** Significantly different at P=0.01
* Significantly different at P=0.05
SL= Stress level, Cul= cultivar

Appendix 8.3b Analysis of variance for stomatal conductance between two tomato cultivars, with and without water stress and their interactions under green house condition at 50% flowering stage.

Sources of variations	SS	DF	MS	F	Fprob
SL	645440.042	1	645440.042	77.769	0.000**
Cul	43409.946	1	43409.946	5.230	0.025*
SLx Cul	6653.507	1	6653.507	0.802	0.373ns
Error	730351.165	88	8299.445		
Total	3342098.638	96			

R Squared = 0.490
** Significantly different at P=0.01
* Significantly different at P=0.05
SL= Stress level, Cul= cultivar

Appendix 8.3c Analysis of variance for stomatal conductance between two tomato cultivars, with and without water stress and their interactions under field condition at 50% fruiting stage.

Sources of variations	SS	DF	MS	F	Fprob
SL	1662634.400	1	1662634.400	418.824	0.000**
Cul	88792.335	1	88792.335	22.367	0.000**
SLx Cul	121282.384	1	121282.384	30.551	0.000**
Error	349339.678	88	3969.769		
Total	2393528.593	96			

R Squared =0 .854
** Significantly different at P=0.01
SL= Stress level, Cul= cultivar

Appendix 8.3d Analysis of variance for stomatal conductance between two tomato cultivars, with and without water stress and their interactions under green house condition at 50% fruiting stage.

Sources of variations	SS	DF	MS	F	Fprob
SL	2461793.788	1	2461793.788	448.435	0.000**
Cul	919.463	1	919.463	0.167	0.683ns
SLx Cul	4716.608	1	4716.608	0.859	0.357ns
Error	483097.343	88	5489.743		
Total	7359763.150	96			

R Squared =0.857
** Significantly different at P=0.01
SL= Stress level, Cul= cultivar

Appendix 8.4a Analysis of variance 50% days to flowering between two tomato cultivars, with and without water stress under field condition.

Sources of variations	SS	DF	MS	F	Fprob
SL	1014.000	1	1014.000	-	-ns
Cul	6.000	1	6.000	-	-ns
SLx Cul	6.000	1	6.000	-	-ns
Error	.000	88	.000		
Total	97800.000	96			

R Squared = 1.000
SL= Stress level, Cul= cultivar

Appendix 8.4b Analysis of variance 50% days between two tomato cultivars, with and without water stress under green house condition.

Sources of variations	SS	DF	MS	F	Fprob
SL	486.000	1	486.000	-	-ns
Cul	150.000	1	150.000	-	-ns
SLx Cul	6.000	1	6.000	-	-ns
Error	.000	88	.000		
Total	163992.000	96			

R Squared = 1.000
SL= Stress level, Cul= cultivar

Appendix 8.5a Analysis of variance plant height between two tomato cultivars, with and without water stress under field condition.

Sources of variations	SS	DF	MS	F	Fprob
SL	2344.327	1	2344.327	120.736	0.000**
Cul	614.082	1	614.082	31.626	0.000**
SLx Cul	10.935	1	10.935	0.563	0.455ns
Error	1708.690	88	19.417		
Total	87046.200	96			

R Squared =0.635
SL= Stress level, Cul= cultivar

Appendix 8.5b Analysis of variance plant height between two tomato cultivars, with and without water stress under green house condition.

Sources of variations	SS	DF	MS	F	Fprob
SL	2799.360	1	2799.360	154.175	0.000**
Cul	214.802	1	214.802	11.830	0.001**
SLx Cul	31.740	1	31.740	1.748	0.190ns
Error	1597.817	88	18.157		
Total	159751.400	96			

R Squared = 0.656
** Significantly different at P=0.01
SL= Stress level, Cul= cultivar

Appendix 8.6a Analysis of variance number of fruits per plant between two tomato cultivars, with and without water stress under field condition.

Sources of variations	SS	DF	MS	F	Fprob
SL	726.000	1	726.000	356.253	0.000**
Cul	0.000	1	0.000	0.000	1.000ns
SLx Cul	6.000	1	6.000	2.944	0.090ns
Error	179.333	88	2.038		
Total	911.333	96			

R Squared =0 .803
** Significantly different at P=0.01
SL= Stress level, Cul= cultivar

Appendix 8.6b Analysis of variance number of fruits per plant between two tomato cultivars, with and without water stress under green house condition.

Sources of variations	SS	DF	MS	F	Fprob
SL	1584.375	1	1584.375	597.109	0.000**
Cul	0.375	1	0.375	0.141	0.708ns
SLx Cul	0.375	1	0.375	0.141	0.708ns
Error	233.500	88	2.653		
Total	9274.000	96			

R Squared = 0.872
** Significantly different at P=0.01
SL= Stress level, Cul= cultivar

Appendix 8.7a Analysis of variance fruits yield per plant between two tomato cultivars, with and without water stress under field condition.

Sources of variations	SS	DF	MS	F	Fprob
SL	1105039.793	1	1105039.793	693.235	0.000**
Cul	10968.368	1	10968.368	6.881	0.010**
SLx Cul	674.690	1	674.690	0.423	0.517ns
Error	140274.892	88	1594.033		
Total	1256957.743	96			

R Squared = 0.888
** Significantly different at P=0.01
SL= Stress level, Cul= cultivar

Appendix 8.7b Analysis of variance fruits yield per plant between two tomato cultivars, with and without water stress under green house condition.

Sources of variations	SS	DF	MS	F	Fprob
SL	2206920.072	1	2206920.072	526.148	0.000**
Cul	33832.550	1	33832.550	8.066	0.006**
SLx Cul	8688.337	1	8688.337	02.071	0.154ns
Error	233.500	88	2.653		
Total	9274.000	96			

R Squared = 0.859
** Significantly different at P=0.01
SL= Stress level, Cul= cultivar

2. Calculations

8.8 Length equivalents

To convert	Multiply by	Obtain
Inches	2.540	Centimeters (cm)
Foot	30.48	Centimeters (cm)