Response of Navel orange trees to timed partial root zone drying in northern Zimbabwe

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A thesis submitted in partial fulfillment of the
requirements for the degree of
Master of Science in Agricultural Meteorology.

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May, 2010

Abstract

Navel orange trees (*Citrus sinensis* (L.)Osbeck) were drip irrigated in an 8 hectare commercial orchard at Mazowe Citrus Estate (Mazowe Citrus Estate: block U5A) in the 2009/2010 season. We investigated the effects of partial root zone drying (PRD) applied at different periods of fruit growth on fruit growth rates, fruit yield, fruit quality and water use efficiency. This was done in order to determine the importance of the timing of PRD application on physiological and agronomic citrus response under semi arid conditions. Partial root zone drying (PRD) is an irrigation system which allows a reduction of seasonal irrigation volume near the 50 percent of a well watered crop, and improves fruit quality parameters, without significant yield reduction. In the PRD technique only half of the root system is irrigated, the other half is maintained in drying soil. After 10-15 days, the wet and the dry root zones are inverted. This system of watering would allow separating some positive effects of water deficit (better fruit quality, reduction of transpiration losses) from the negative effects such as fruit yield reduction.

The first part of the project entailed monitoring of sap flow rates over a period of seven days (DOY 135-DOY 141). This exercise gave a guide to the typical sap flow rates attained under different PRD and non PRD treatments. This information was useful in timing of PRD. Yields attained under the different treatments were analysed and related to the sap flow rates. The PRD treatment gave lower sap flow rates and higher yields. The PRD treatment used water more efficiently compared to the other two treatments.

In the second part of the project, six irrigation treatments were applied: Control which applied water one side of tree irrigating according to ETo data from the automatic weather station and, the growers practice, which is the convectional drip irrigation, PRD which applied 50 percent water as that of the control, PRD 50% stage 2, PRD 50 % stage 3, PRD 75% stage 2, 50% stage 3.The treatments received different amounts of irrigation water due to the different irrigation durations in each treatment. Fruit growth rates during the experimental period were not significantly affected by timing PRD treatments. There were no significant treatments effects on fruit yield and fruit quality was significantly affected by timing PRD. Water use efficiency was lowered when timing of PRD was introduced but favourable results were obtained. Fruit size was significantly affected by crop load.

Dedication

To my loving husband Para.

Acknowledgements

I would like to express my gratitude to the individuals, groups and organisations that helped in making this whole project a sound success.

First I would like to acknowledge my appreciation to the help rendered to me by my supervisors, particularly Dr T. Mhizha, Mr E. Mashonjowa and Mr B Chipindu who always chipped in with brilliant ideas and motivation in addition to their excellent academic leadership qualities. I would also like to thank Dr Dzikiti for all the support and advice he gave me, thank you.

I am also grateful to Mazowe Citrus Estate and its staff for allowing me to use their productive trees for research purposes. Special mention goes to Mr Tsamba, Mr Whisk, Mr Mashanda, Mr Chakutamanzi and Mr Maoneke who were always ready to offer help upon request.

I would like to give thanks to the whole MAGM group 2008-2010, for their support throughout this work. Special mention goes to my classmates, Mr S. Zirebwa, Mr F. Simba, Mr J.Masanganise, Mr N. Zinyengere, Miss N. Nyamutata, Mr S.Grey and Mr J. Chayangira. We worked as a family, thank you guys. I also thank Mr Gwara, Mr Muroiwa and Mr Mutungura who were always willing to sacrifice their time to drive me to the research site.

Finally, I say thank you to my family members for their support, especially Para, my life partner, for being the person that he is.

MAY GOD BLESS YOU ALL

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LIST OF SYMBOLS AND ABBREVIATIONS

Abbreviations

ABA	abscisic acid
CR	capillary rise
DOY	Julian day of year
DP	deep percolation
ET	crop evapotranspiration
ET_c	evapotranspiration under standard conditions
ET_o	potential evapotranspiration
Epan	pan evaporation
FAO	Food and Agriculture Organisation
Ha	hectares
I	irrigation
LAI	leaf area index
MCE	Mazowe Citrus Estate
Pr	precipitation
PRD	partial root zone drying

R	rainfall
RO	run off
SF	scaling factor
SF_{in}	sub surface flow (in)
SF_{out}	subsurface flow (out)
T	mean daily air temperature (^oC)
TA	Total Acids
TDP	thermal dissipation probe
TSS	Total Soluble Solids
U_2	wind speed at 2 m above ground level
WUE	water use efficiency
ΔSW	change in soil moisture content

Roman symbols

Symbol	Description	Unit
A_s	conducting sapwood area	(cm^2)
A_{st}	stem cross sectional area	(cm^2)
e_s	saturation vapour pressure	(kPa)
e_a	vapour pressure of the air	(kPa)
F	stem sap flow rate	(gh^{-1})
K	dimensionless flow constant for computing sap velocity in TDPs	(-)
K_c	crop coefficient	(-)
K_p	pan coefficient	(-)
K_{sh}	radial sheath conductance of heat balance sap flow gauges	(WmV^{-1})
K_{st}	thermal conductivity of wood	($Wm^{-1}K^{-1}$)
n	number of drip emitters	(-)
P_{in}	power input to the heat balance	(J)
q_f	heat transported by the moving sap stream	(J)

q_r	radial heat transport from heat balance sap flow gauges	(J)
q_v	axial heat transport from the heat balance sap flow gauges	(J)
dTm	maximum temperature difference between TDP probes	(^oC)

Greek symbols

Symbol	**Description**	**Unit**
Δ	slope of the temperature difference between TDP probes	(^oC)
θ_v	volumetric water content	(cm^3cm^{-3})
γ	psychometric constant	(kPa^oC^{-1})

CHAPTER 1

INTRODUCTION

1.0 Background

Zimbabwe is a landlocked country in the Southern Africa region. Climatic conditions are largely sub-tropical with one rainy season between November and March. Rainfall reliability decreases from North to South and also from East to West. Only 37% of the country receives rainfall considered adequate for agriculture. In Northern Zimbabwe rainfall is unevenly distributed at different parts of the year, with marked dry and wet seasons. To stabilize fruit production and quality, it is necessary to supply adequate irrigation in the dry season, and proper drainage during the wet season. It is important to provide the right amount of water at different growth stages, to enhance the growth of citrus trees. Citrus fruit production in Zimbabwe is done mainly in areas within or surrounding the Limpopo valley, the Save valley and the Mazowe valley. Commercial production is primarily for export to fresh fruit market, but due to lack of expertise and resources, the small-scale farmers fail to produce quality fruit for export (Sithole, 2005). With more proper farming practices, especially by the small-scale farmers, the sector has the potential to grow and increase its exports, (Sithole, 2005).

Citrus plays an important role to the economy of Zimbabwe. The sustainable production of citrus depends on the availability of adequate water throughout the year since citrus is an evergreen crop. The increasing competition for water between citrus growers, recreation, industrial and domestic users means that less water is becoming available for irrigating large citrus plantations, such as the Mazowe Citrus Estate in Northern Zimbabwe, (Dzikiti et al., 2007). Sustainable production of citrus, thus, requires not only the efficient management of the limited water resources, but also the development of new irrigation strategies which lead to improved water use efficiency.

1.1 Partial Root Zone drying (PRD)

Partial root zone drying (PRD) is the practice of alternately wetting and drying the root zone on two sides of the tree and is employed year-round. In the PRD technique only half of the root zone is irrigated, the other half is maintained in drying soil. After 10-15 days, the wet and the dry root zone are inverted allowing the former 'wet' zone to dry while the 'dry' zone is irrigated (Dry and Loveys, 1998). Partial Root Zone drying is an irrigation strategy designed to increase water-use efficiency in fruit tree crops to further reduce production costs. The method limits vegetative shoots growth in favour of crop development with the goal that neither the current or return yield is negatively affected (C.J.Lovatt et al., 2008).This system of watering would allow separating some positive effects of water deficit (better fruit quality, restriction of side shoot growth and reduction of the transpiration losses) from the negative effects such as fruit yield reduction (Sirigu *et al*., 2006).

PRD is based on the fact that the hormone abscissic acid (ABA), a plant growth hormone is produced in roots subjected to water-deficit on the dry side of the tree and travels to the leaves, where it closes the stomates (C.J.Lovatt et al., 2008). Normally, the closure of stomata in response to drying soil conditions serves to protect leaf tissue from excessive loss of moisture, thereby conserving water by reducing transpiration. When part of the root zone dries out the level of abscissic acid ABA in the plant increases. This sends a message to the plant leaves to close the stomata as a response to water stress, reducing shoot growth and transpiration from the leaf surface.

However, because other roots still have access to water, the plant continues to grow and fruit development is not significantly affected. Alternating the wet and dry zones of the roots means that repeated surges of ABA are delivered to the shoots, maintaining conditions of reduced shoot growth and reduced transpiration, but with no significant effects on flowering and fruit development.

The application of partial root zone drying (PRD) technique offers the potential of reducing water usage whilst not affecting crop yields if properly timed (Dzikiti et al., 2007; Loveys et al., 2000).The PRD technique was developed on the basis of the mechanisms controlling transpiration, and requires that approximately half of the root system be always in a dry or drying state while the remainder is irrigated. In addition, recent studies (Hutton et al., 2007; Treeby et al., 2007) have suggested that proper timing of PRD technique can adjust the alternate bearing tendencies of some citrus cultivars.

1.2 Motivation

Water supply is limited worldwide (Postel, 1998) and there is an urgent need to identify and adopt effective irrigation management strategies. As irrigation of agricultural lands accounts for over 85% of water usage worldwide (van Schilfgaarde, 1994), even a relatively minor reduction in irrigation water could substantially increase the water available for other purposes (Zegbe-Dominguez et al., 2003). In the face of increasing scarcity for water due to global climate change and variability and rising demand, new innovations to save water in citrus irrigation are needed without loss of yield.

More research has to be done on citrus production to improve quality, yield and at the same time conserving water. More fruit has to be produced using a limited amount of water without compromising on quality so that a large proportion of the total produce qualifies for the lucrative export market (Gross et al., 2002).

Partial root zone drying has been looked into in various crops. As such cherries, apricots, apples, pears, Valencia and navel oranges were assessed for their response to partial drying of the root system. Plant water use (stomatal conductance) was reduced by between 30% and 40% when half of the root system remained unirrigated (NPSI Factsheet, 2005).

This study seeks to investigate the potential benefits of timing of PRD to the productivity of Navel orange trees growing in the seasonally arid tropics in Northern Zimbabwe.

1.3 Objectives

The main objective of the research was to study the effects of timing of PRD on fruit growth and yield and water use efficiency, with special emphasis on the following specific objectives:

1. To quantify transpiration rates of navel citrus trees under PRD.
2. To provide quantitative information on the dynamics of seasonal water use under PRD regimes.
3. To study the effects of timing of PRD on navel fruit growth, yield and quality.
4. Evaluate total water use by navel trees under PRD.

1.4 Thesis Layout

The thesis is divided into five chapters. Chapter one gives the background of the study. It also gives the justification for the research that is being carried out as well as the objectives of the study. Chapter two reviews some relevant literature of the research project. Chapter 3 is a detailed description of the materials and methods used in acquiring data and analysing it to draw conclusions on the above mentioned objectives. Chapter 4 gives the results and interpretation of the research findings. Chapter 5 discusses the conclusions drawn from the results and the recommendations for further research in related work. References and appendices are provided at the end of the thesis.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

The effective use of irrigation water has become a key component in the production of field crops and high-quality fruit crops in arid and semi-arid areas. Irrigation has been the major driving force for agricultural development in these areas for some time. Efficient water use has become an important issue in recent years because the lack of available water resources in some areas is increasingly becoming a serious problem. Much effort has been spent on developing techniques such as partial root-zone drying (PRD) to improve field and fruit crop water use efficiency (WUE).

2.1 Citrus Production in Zimbabwe

Citrus has been one of Zimbabwe's major successes. The sector accounts for 55% of total horticultural exports by volume and 10% by value (Food and Agriculture Organisation, 2003). Most of the fruit is exported to Europe and the Middle East. There has been a steady increase in the citrus production from 1980s and a tremendous expansion in citrus production for export occurred from the mid 1990s through to the year 2001. This increased production has been a result of the increased demand for citrus fruits in the international market, which has seen exports of citrus fruits becoming one of the dominant exports in the country's export basket (FAO, 2003). The challenge to the citrus producers in Zimbabwe is to continue producing more fruit for the export market.

2.1.1 Mazowe Citrus Estate

Mazowe Citrus Estate falls in the Mazowe valley with the Glendale, Bindura, and Shamva farming areas. The area is relatively cooler which enables the growth of different citrus varieties.

Mazowe Citrus Estate is one of the major citrus growers in Zimbabwe, with a total of 660.1 ha under citrus plantation. Navels, lemons, and some soft citrus varieties along with the Valencias are grown in MCE. Oranges contribute about 73% of the total hactarage, of which 40% are Navels.

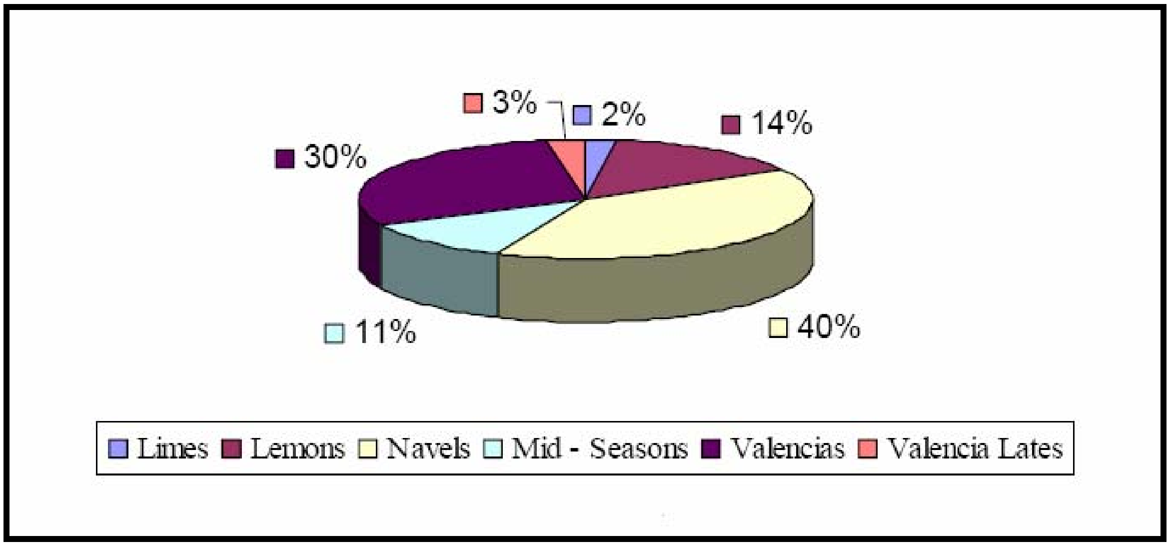

Fig 2.1 Mazowe Citrus Estate percentage area distribution by citrus variety (adapted from Sithole, 2005)

The fruit produced at MCE are primarily for the fresh fruit export market (Sithole, 2005). Only third grade fruit is sold on the local market either as fresh fruit or crushed for juicing (Sithole, 2005). However the fresh fruit has flooded the market and this is affecting the prices and as a result, juicing has become more profitable. Other local producers who fail to export their fruit also sell it to MCE for juicing.

2.2 The Citrus Crop

Citrus fruit trees are of relatively small size, evergreen and perennial growth habit. They can reach height ranging from 5-15 m tall with spiny shoots and alternately arranged evergreen leaves with an entire margin. The flowers are solitary or in small corymbs, each flower 2-4 cm in diameter, with five (rarely four) white petals and numerous stamens. The fruit is a hesperidium, a specialised berry with a leathery rind surrounding segments filled with pulp vesicles. Though broad leaved, they are evergreen and do not drop leaves except when stressed.

The citrus trees belong to the C_3 group of plants with photosynthetic rates lower than those of C_4 plant. Even among the C_3 group, citrus trees are in the low activity range being considerably lower than annual crop plants and lower still compared with deciduous fruit trees e.g. grape (*Vitis vinifera* L) (Spiegel-Roy and Goldschmidt, 1996). This perennial crop does not tolerate cold climate and is therefore normally cultivated in the area situated at latitude between 40^o North and 40^o South up to 1800 m altitude in the tropics and up to 750 m altitude in the subtropics. They are also grown in the Mediterranean type climates.

Generally, citrus start bearing fruit 3-5 years from planting, but economic yields start from the fifth year and the trees may take 8 to 10 years to achieve full productivity. Fruit can be harvested 5-6 months from flowering depending on the variety and the environment. Only a small percentage of flowers produce fruit (Lovatt et al., 1984). Citrus trees require a rich, well drained soil. The trees are also sensitive to high salt concentration in the soil. Citrus growing needs periodical fertilisation and irrigation of the soil, (Zekri et al., 2003)

2.2.1 Flowering

Fruit growth in citrus follows a sigmoid pattern. Maximum shoot initiation occurs during late winter and spring with only sporadic growth occurring during summer and autumn (December and May) (Dzikiti, 2007).The shoots produced in spring are the most important as these form the sites on which flowers develop.

2.2.2 Fruit Development and Maturation

According to Bain (1958) development of citrus fruit is divided into three major stages. These are cell division, cell expansion and fruit maturation. In reality these stages are not clearly distinguishable but they overlap considerably (Dzikiti, 2007). Stage 1, thus cell division determines the total cell number of each fruit (Sithole, 2005). This phase in turn determines the ultimate fruit size (Davis and Albrigo, 1994).Stage 1 is assumed to commence at fruit set where fruit set is the process through which the flower ovary adheres to the tree and becomes fruit. Stage 1 extends from early October to early December in northern Zimbabwe (Dzikiti, 2007). This takes about 1-1.5 months following bloom depending on cultivar and prevailing climatic conditions. The intensity of the flowering is also thought to affect the final fruit size with high flower intensities leading to smaller sized flowers and ultimately smaller fruits (Guardiolla, 1997).

Usually the citrus trees produce more flowers than the number that actually sets and produce harvestable fruits (0.1-3% of the total) (Dzikiti, 2007). The increase in fruit size during stage 1 is mainly due to the growth of the peel consisting mainly of cell division but there is already an element of cell expansion which is stage 2 (Dzikiti, 2007). Cell expansion leads to increased cell size and total soluble solids (TSS) (Sithole, 2005). For sweet oranges in lowland tropics, stage 2 takes 3-4 months (Sithole, 2005). In northern Zimbabwe the cell expansion phase extends from December until April or early May depending on cultivar. During this period the fruit may increase in volume by as much as 1000 times (Sithole, 2005).

During the final phase which is the maturation and ripening (stage 3), the peel colour changes from green to yellow. Fruit growth levels off and there is a gradual increase in the total soluble solids and a decline in total acidity of the fruit juice (Sithole, 2005).

Soil moisture and temperature are the major determining factors of fruit growth in each climatic region, especially during the third stage. High mean temperature favour rapid fruit growth rates while low mean temperatures low or down the growth rate (Davis and Albrigo, 1994). Adequate soil moisture during the cell expansion phase significantly improves fruit set.

2.2.3 Citrus Tree Composition

A typical citrus tree is composed of approximately 60% water and 40% dry matter. The dry matter portion averages approximately 95% carbon based compounds, 2% calcium, 1% nitrogen and small amounts of many other nutrients. Specifically, leaves and roots contain approximately 70% water, while fruit contains about 85% water (Syversten et al., 2008). The woody portions of the tree, including the trunk, limbs and branches contain about 50% water. In addition all plants transpire far more water from leaves to the air than the water they contain. To ensure that this large water requirement to support transpiration is met, growers should consider both rainfall and irrigation sources as needed replacements for lost water (Syversten et al., 2008).

2.2.4 Citrus Tree Water Uptake

Most citrus trees develop a tap root. The lateral roots form a horizontal mat of feeding roots with weakly developed root hairs. Root development is largely dependent on the type of rootstock used and on the characteristics of the soil profile. Rooting depth varies between 1.2 and 2 m. In general, 60 percent of the roots are found in the first 0.5 m, 30 percent in the second 0.5 m and 10 percent below 1 m. Where water supply is adequate, normally 100 percent of the water is extracted from the first 1.2 to 1.6 m, but under dry conditions the depth of water extracted below this depth increases (Syversten et al ., 2008).

2.2.5 Internal fruit quality

Fruit quality is affected by several factors including cultivar, rootstock, climate, soil, pests, irrigation, and nutrition (Zekri et al., 2003). Fruit quality is generally classified into two parts, the external quality (colour, shape, size and blemishes) and the internal quality (juice content, TSS, TA, and seedless). Consumers want high quality fruit and the competition for fruit from different countries in the globalised economy in the world is getting higher and higher. Each market can determine the most worthy characteristics of the fruit.

A good internal quality, coupled with a good external quality, leads consumers to the habit of buying the fruit since it determines fruit edibility. The flavor and palatability of citrus fruit is a function of relative levels of TSS, TA and various aromatic or bitter compounds (Zekri *et al.,* 2003). The juiciness and toughness of the pulp vesicles also affect fruit palatability of fresh citrus eaten out of hand. Internal quality is, to a large extent, influenced by soil water since water comprises a major portion of the fruit mass (85-90 % by weight). Temperature is also an important parameter in determining the final internal quality. Carbohydrates constitute 75-80 % of the TSS (Davies and Albrigo, 1994). Regulation of carbohydrate loading into the citrus fruit has a great impact on the internal fruit quality. TSS accumulate most rapidly under high temperatures in lowland tropical areas and much slower in the cold highland tropical areas (Davies and Albrigo, 1994). High temperatures also favour the rapid decline in TA while low temperatures cause a slower and limited decline in TA. The final TA content is primarily a function of temperature and the respiration of organic acids at these temperatures. The ratio of TSS: TA is a primary determinant of fruit edibility and is linked to maturity (Davies and Albrigo, 1994). In sweet oranges for example, attainment of a minimum TSS: TA ratio of 7-9:1 is an indication of fruit maturity depending on location and local standards.

2.3 Fruit abscission

Physiological fruit drop is the abscission of fruit-lets as they approach a diameter of 5-20 mm. It occurs in November and December in the Southern Hemisphere and in June and July in the Northern Hemisphere due to a combination of different factors (Davies and Albrigo, 1994). It is mostly due to competition among fruit-lets for carbohydrates, water, hormones and other metabolites necessary for fruit growth and development. This problem is greatly increased by stress, particularly water deficit and/ or high temperature. Since a number of factors combine, it is very difficult to correct fruit drop.

In citrus production, fruit drop is a natural process in which the tree sheds off excess fruit (Spiegel-Roy and Goldschmidt, 1996). Annual amount of fruit loss is estimated at 10-20 % with variations occurring with climate and crop load. The Navel oranges are mostly affected by fruit drop due to their sensitivity to water stress. Extensive fruit drop can reduce fruit numbers in Navels by as much as 35 % (Gat et al., 1997).

The November fruit drop is mainly due to competition between fruit-lets and young leaves for photosynthetic products, a factor worsened by environmental stress, especially moisture and heat stress. If water stress occurs in September or October, then few fruit will set (FAO/AGL, 2002). Similarly, if it occurs in November, December or January, then a large portion of the fruit that has set will drop. It has also been discovered that extremely high temperatures of above 40^{o}C also cause excessive fruit drop, especially in the Navel oranges since they are least adapted to stress than any other citrus varieties (Davies, 1986). In general this physiological drop is usually most severe where leaf temperatures may be above 35^{o}C and where water stress is a problem. This combination is believed to cause stomatal closure with a consequent reduction in net CO_2 assimilation. As a result the fruit maintain a negative carbon balance as photosynthetic rates are reduced and fruit abscission occurs (Spiegel-Roy and Goldschmidt, 1996). Differences in carbohydrate or hormone levels within the fruit may also be involved. In areas of very high temperatures, overhead irrigation has been seen to reduce the effect.

2.4 The effects of Climate on Citrus Crop

Climate has a significant effect on citrus growth and development. Climatic factors are both limiting and coactive (Davis and Albrigo, 1994) For example low temperature and water are major limiting factors but temperature and water stress may also act together to reduce or enhance growth or productivity (Lardsberg and Cutting, 1997). Therefore it is vital for the citrus growers to optimise climatic factors that are coactive and then reduce the risk of limiting factors.

2.4.1 Temperature and fruit development

Temperature is an important environmental parameter in citrus fruit production. A higher temperature results in more heat units, calculated as the amount of time in days multiplied by the average temperature difference from the minimum for citrus vegetative growth taken usually as 12.5 °C (Mendel, 1969). Heat unit accumulation impacts on the phenological development calendar and fruit quality. As a result, if water and nutrients are not limiting, annual heat unit accumulation is strongly correlated with growth rate and quality.

An average temperature of less than 24 °C is required to induce flowering (Davies and Albrigo, 1994). The minimum threshold for flowering is about 9.4 °C. The rate of flower development is positively correlated with degree days (Lovatt et al., 1984). Fruit growth rate in each climatic region is primarily a function of temperature during each developmental stage. The highest mean temperatures provide the fastest fruit growth rates. On the other hand, extremely high temperatures of greater than 40 °C can cause excessive fruit drop especially from the navel oranges because they are more sensitive to heat stress than most other citrus species (Davies, 1986).

Temperature also affects fruit quality, both external and internal. High temperatures interfere with the loss of chlorophyll and build up of carotenoids at maturity. As a result, oranges fail to attain an attractive rind colour and remain pale. High temperatures, in conjunction with high humidity, make fruit more susceptible to blemishes (Gat et al., 1997). In extreme summer temperatures, heat damage in the form of sunburned peel, dried flesh, reduced fruit size and increased granulation is often found on fruit exposed to the sun. Fruit developing in hot climates have high total soluble solids (TSS), an advantage for processing industry. However, such fruit are too low in acid resulting in poor edible quality. Therefore subtropical areas with cooler temperatures are preferred for cultivation of fresh fruit.

2.5 Water Productivity in Citrus

Water use efficiency (WUE) is the ratio of net carbon dioxide assimilation to water use (Bacon, 2004). Carbon dioxide assimilation may be in terms of net carbon dioxide exchange, dry matter growth and economic yield while water use may be determined by mass or molar unit (Bacon, 2004). Improvement of water use efficiency in crop plants is important for almost all agricultural practices around the world. Water use efficiency of a plant is determined by the respective rate of water loss, carbon dioxide uptake and respiration (Kijne et al, 2003). Water use efficiency is strongly related to photosynthetic activity and transpiration efficiency, which can be controlled at some degrees by agronomic approaches, such as irrigation, mulching, tillage and crop spacing (Monneveux et al., 2006). Therefore, it could be expected to improve water use efficiency by agronomic practices.

The information on the water use efficiency of citrus trees under different irrigation regimes can be used by citrus growers to make an informed decision to decide on the best irrigation regime that uses less water and at the same time giving more fruit. Irrigation techniques that seek to improve water use efficiency are designed to optimize the stomatal aperture so that the carbon gain by the plant outweighs water loss as the stomata are the main pathway for the diffusion of carbon dioxide into the plant and the loss of water from the plant (Dzikiti, 2007).

2.6 Irrigation of Citrus Trees

2.6.1 Crop water requirement

Crop water requirement is defined as the amount of water required to compensate the water loss from a cropped field and depends on the amount of solar radiation and stage of plant growth. The higher the solar radiation, the higher the evapotranspiration from plant surfaces will be. In winter, water loss due to transpiration from leaves will be less than that of summer light conditions. Younger plants require less water when compared to fully grown, mature crops. Water is lost in a cropped field from the soil surface by evaporation and by the transpiration process of the plants.

To stabilize fruit production and quality, it is necessary to supply adequate water through irrigation in the dry season, and proper drainage during the wet season. It is important to provide the right amount of water at different growth stages, to enhance the growth of citrus trees.

Citrus trees are evergreens and thus transpire throughout the year. Water requirements for high production vary with climate, ground cover, clean cultivation or no weed control, species and rootstock. As a perennial crop the response of citrus trees to water supply at a particular period of development will depend greatly on the level of water supply prior to that period during the same growing season and also the level of water supply during previous growing seasons.

When water is insufficient, growth is retarded, leaves curl and drop, young fruit fall and fruit that mature are deficient in juice and inferior in quality. When the soil water depletion reaches permanent wilting point, tree growth is terminated and subsequently affects fruit and leaves, followed by twigs, branches and eventually the whole tree. For mature trees, the growth vigour determines the replacement rate of fruit-bearing branches. Any effect of water deficit on root and leaf development may impair the number and size of fruit later in the season.

2.6.2 Irrigation Methods

Irrigation for citrus orchards should match, not only the growth and development stages of the trees, but also the topography of the orchard, this includes soil properties. It should also take into account environmental factor such as temperature, humidity, photoperiod and wind. The amount of irrigation water needed depends on the water-holding capacity of the soil, the amount of rainfall, and the rate of transpiration of the trees. Here are various methods of irrigation and these include surface irrigation, sprinkler irrigation and drip irrigation.

2.6.2.1 Surface Irrigation

If the orchard is flat and water is easy to obtain, surface irrigation is used. In surface irrigation systems water moves over and across the land by simple gravity flow. The most common surface irrigation method used is furrow irrigation, where there are several furrows between the tree rows. Furrows should be filled with water and then drained, to ensure that the entire root system receives a sufficient amount of water. There is also check irrigation, where there are basins containing one or more trees. There is also flood irrigation where trees are planted on beds or ridges. Because of uneven water distribution and the difficulty of applying small amounts of water, the importance of surface irrigation for citrus is decreasing.

2.6.2.2Sprinkler Irrigation

This is a planned irrigation system in which water is applied by means of perforated pipes or nozzles operated under pressure so as to form a spray pattern. Water is piped to one or more central locations within the field and distributed by overhead high-pressure sprinklers or guns. Sprinkler irrigation may provide a more uniform distribution of water and there is a possibility of applying the exact depth of required water.

2.6.2.3 Drip Irrigation

In drip irrigation, water is delivered at or near the root zone of plant, drop by drop. This method can be the most water-efficient method of irrigation, if managed properly, since evaporation and runoff are minimized (Synder et al*.,* 2005). Water is sent through plastic pipes with emitters that are either laid along the rows of crops or even buried along their root lines. It is operated under low pressure. Deep percolation, where water moves below the root zone, can occur if a drip system is operated for too long a duration or if the delivery rate is too high. With drip irrigation system, water savings maybe obtained because water is applied only to the root zone, leaving the remaining part of the soil dry.

2.7 Irrigation Scheduling

Irrigation scheduling was first introduced in the 1960s and was defined as the method of measuring soil water status for deciding when to irrigate (Clyma, 1996), thus irrigation scheduling deals with how much and when to irrigate a crop. It consists of applying the right amount of water at the right time. Irrigation scheduling methods are based on three approaches, namely, crop monitoring, soil monitoring and water balance technique (Blonquist et al., 2006).

2.7.1 Plant water based methods

Recently the monitoring of plant water has been advocated and techniques involving plant water measurement as a response to soil water especially water stress (Jones, 2004). The major drawback of this method is that the decision to irrigate is made after the plant has suffered some amount of water stress, which may adversely affect the crop yield. Calibration is often necessary to determine the control threshold at which irrigation should commence (Jones, 2004).

2.7.2 Soil water content based methods

Irrigation scheduling can be based on soil water content measurement where soil moisture status, water content or potential is measured directly to determine the need for irrigation. Measurement and estimates of water content for use in irrigation scheduling can be performed via gravimetric, neutron scattering, and tensiometer methods. In recent years, water content estimates have advanced to include electromagnetic techniques such as the time domain reflectometry (TDR) (Topp et al., 2001, Robinson et al., 2003).

2.7.3 Evaporation Pan

The evaporation rate can also be obtained from Class A pans filled with water. The use of the evaporation pans provide a practical tool for the accurate scheduling in the field. The pan provides a measurement of the integrated effects of radiation, wind, temperature and humidity on the evaporation from an open water surface. In the absence of rain, the amount of water evaporated during a period (mm/day) corresponds with the decrease water depth in that period.

Although there are differences between pan-evaporation and the evapotranspiration of cropped surfaces, the pan evaporation is related to the reference evapotranspiration by an empirically derived pan coefficient: The evaporation measured from the pan (Epan) is multiplied by the pan coefficient (K_{pan}) to obtain the ET_o (reference evapotranspiration).

$ET_o = K_pE_{pan}$ …..(2.1)

Where ET_o = the reference Evapotranspiration (mm/day)

K_p = the pan coefficient

E_{pan} = the pan evaporation (mm/day)

The pan is sited on a short green grass cover and surrounded by fallow soil which is a green fetch. The pan readings are taken daily in the morning at the same time. If there is any precipitation it is measured as well. Measurements are made in a stilling well that is situated in the pan near one edge. The water should be renewed weekly to eliminate extreme turbidity.

Sources of error include the differences in the energy balance of the pan and that of the trees given the differences in the reflectance of solar radiation between he water surface and the trees. In addition, energy can be lost or gained through the sides of the pan, while the significant storage of heat by the pan ensures that water loss can continue to occur after sunset, while transpiration will have ceased (Dzikiti, 2007). ETo can be multiplied by crop water use Kc for the specific crop, stage and cultural conditions to obtain the crop water requirement.

$ETc = EToKc$ …..(2.2)

The pans require proper recording, maintenance and management (Allen *et al*., 1998).

2.7.4 Soil water balance approach

Alternatively the soil water balance method can be used. Evapotranspiration can be determined by estimating the various components of soil water balance. The method consists of assessing the incoming and outgoing water fluxes into the crop root zone over a certain period. There can be irrigation and precipitation which add water into the root zone. Surface runoff and deep percolation remove water from the root zone. As shown in fig 2.2, water might also be transmitted upwards by capillary rise from a shallow water table towards the root zone, or even transferred horizontally by sub-surface flow in or out of the root zone. If all other fluxes except evapotranspiration can be assessed then evapotranspiration can be deduced from:

$$\Delta SW = (R+I+CR+SF_{in})-(DP+SF_{out}+RO+ET) \quad \text{.....(2.3)}$$

$$ET= R+I+CR+SF_{in}-DP-SF_{out}-RO- \Delta SW \quad \text{.....(2.4)}$$

$$ET= R+I+CR \pm SF \pm \Delta SW -RO- DP \quad \text{.....(2.5)}$$

Where ET= Evapotranspiration

R = rainfall

I = irrigation

CR= capillary rise

DP= deep percolation

RO = run off

SF_{in} = sub surface flow (in)

SF_{out} = subsurface flow out

ΔSW = change in soil moisture content

For short time periods some fluxes e.g. deep percolation, capillary rise and sub-surface flow are difficult to assess. This method can give estimates for longer periods from a week to 10 days (Raes, 2001).

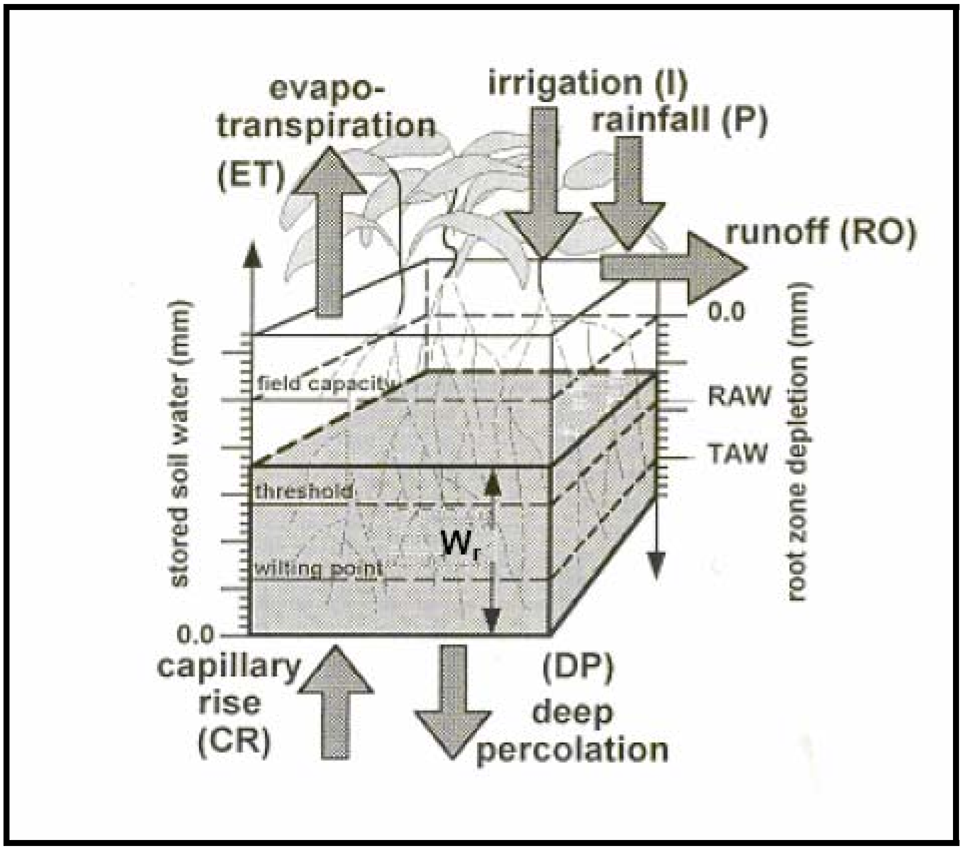

Fig 2.2 Components of the water balance in the root zone for irrigation scheduling (adapted from Raes, 2001).

2.8 Application of PRD in citrus

2.8.1 Response of fruit trees to soil drying

Severe drought stress can significantly limit canopy development by suppressing the vegetative growth which is essential for generating the flowering sites (Bacon, 2004). On the other hand, moderate drought stress often favours reproductive development rather than the vegetative growth in most fruit tress, including the citrus tress (Chambers et al 1981; Hutton, 2000). This is a direct result of a changed resource allocation presumably due to the influence of endogenous chemical signals such as the abscisic acid (ABA) (Dzikiti, 2007). Thus manipulation of the soil water environment with irrigation management can maximise biological activity and be used to improve economic response.

2.8.2 Chemical Signalling

Plant roots can sense the availability of resources (e.g. water and nutrients) in the soil. This information is transmitted to the shoots by chemical signals (e.g. the ABA) so that appropriate control measures can be taken (Dzikiti, 2007). For example, when the soil around the roots is drying the ABA signals generated in the roots in this case, are transported to the leaves via the xylem vessels to the guard cells. The presence of high levels of ABA in the leaves is known to strongly correlate with stomatal closure (Wilkinson et al., 1998; Davies et al., 2002; Mingo and Davies, 2001., Bacon, 2004; Augé and Moore, 2002). In fact, the concentration of ABA signals in the leaves can be used as a proxy measure of the extent of soil drying (Dzikiti, 2007) The ABA controls the stomatal aperture through the adjustment of the guard cell osmotic potential involving the active transport of K^+ and Cl^- ions across the guard cell plasma membranes as described by Assman and Shimazaki (1999).

The abscisic acid (ABA) is arguably the most important stress response hormone involved in the control of water use by plants in drying soil (Wilkinson et al*.,* 1998). This hormone is produced in the roots usually to maintain their growth rate so they can continue to access water when subjected to soil drying. But it can be produced elsewhere within the plant e.g. in the leaves of stressed plants (Dzikiti, 2007).

Soil drying has been reported to raise the pH of the xylem sap such that there is often a good correlation between the soil water status and the xylem sap pH (Wilkinson et al., 1998; Mingo and Davies, 2001). Slovik et al. (1995) provided evidence that ABA penetration to and uptake by the xylem vessels in the root is maximised when the root sap pH is increased. Thus variations in the sap pH can also be used as another measure of soil drying.

2.8.3 Partial Root Zone Drying

The potential agricultural use of this partial root drying technique was first realized by Loveys (1990) who suggested that it might be possible to use the technique as a method for controlling vegetative growth in crops where excess vegetative vigour was a disadvantage. The PRD uses biochemical response of plants to water stress to achieve a balance between vegetative and reproductive development. By doing so, it achieves a secondary goal of significant improvement in production per unit of irrigation water applied (McCarthy et al., 1999).

Implementation of the PRD requires a split root system that vertically divides the root system. Part of the root system is subjected to drying soil, while the other part is irrigated at a given moment. So for PRD to be successful there should be regular switching of the dry and the irrigated side at intervals between 10-21 days depending on the crop.

The continuous drying of part of the root system results in a compensation in growth and functioning by the roots on the wet side, (Mingo and Davis, 2001; Eissentat et al., 2006). The roots in the dry soil remain active, but inactive. They are sustained by the roots in the irrigated soil and they become a sink for assimilates leading to competition with the above ground parts of the tree (Dzikiti, 2007). With time there will be gradual reduction in the xylem concentrations of the chemical signals produced by roots in contact with the drying soil, so the ability to control the stomatal aperture is diminished (Dzikiti, 2007).The water status of the tree is expected to remain unchanged because water is always available on the irrigated part of the root zone to meet the water requirements of the plant.

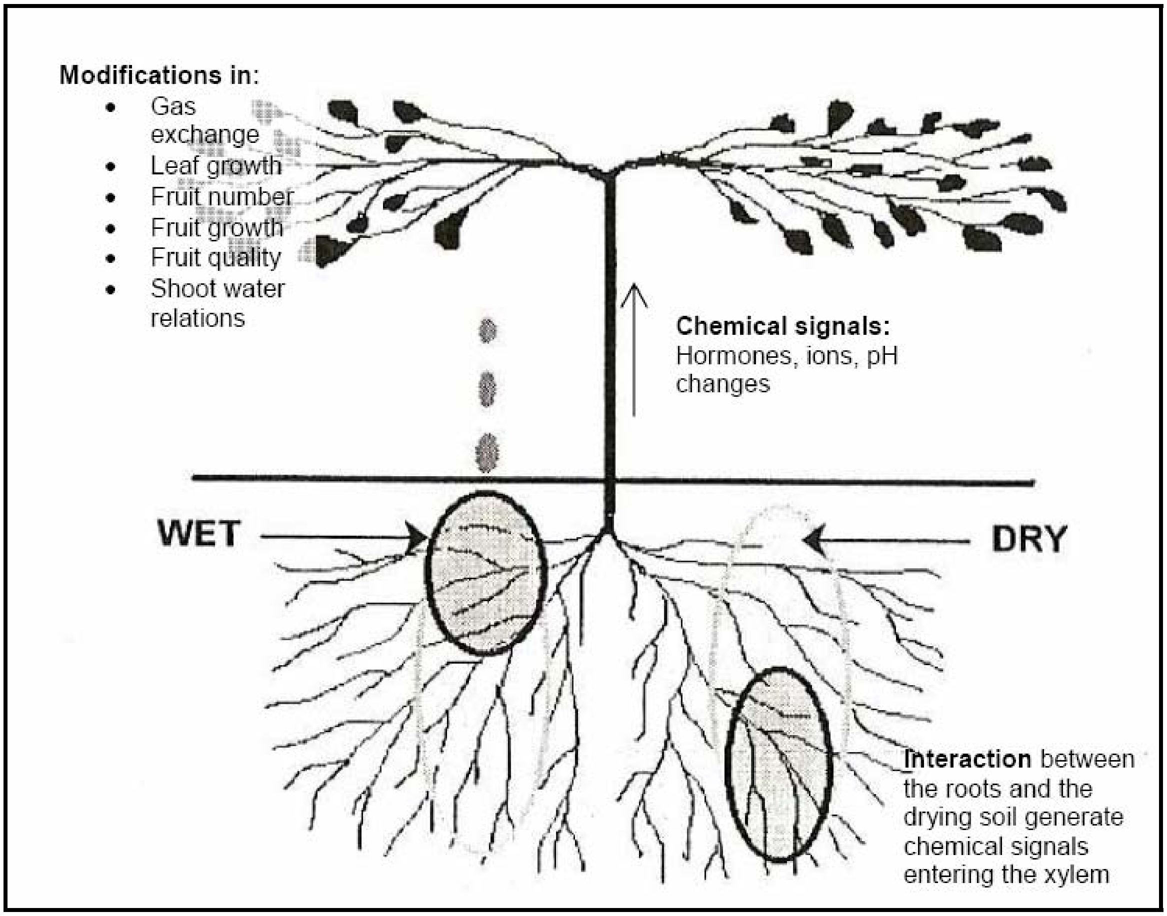

Fig 2.3 Schematic diagram, showing how roots might interact with drying soil to generate chemical signals in the xylem in a typical partial root zone drying setting (adapted from Dzikiti 2007).

Research into the physiological changes that occur during the water stress has led to improved understating of plant response to stress in terms of chemical signals passing from roots to leaves (McCarthy et al., 1999). As soil water availability falls following the cessation of irrigation, ABA is synthesized in the drying roots and transported to the leaves in the transpiration stream (Loveys *et al*., 1999). Stomata respond by reducing aperture thereby restricting water loss. Improvement in WUE results from partial stomatal closure (McCarthy et al., 1999). As carbon dioxide and water vapour share the stomatal pathway through the leaf surface, reduced photosynthesis is an inevitable consequence (Dzikiti, 2007).

2.8.4 Timing of Partial Root Zone Drying

Partial root zone drying was developed in Australia. This technique has been applied successfully to reduce vine vigour (Dry et al., 1996) and water use while maintaining crop yield, and berry size and improving fruit quality compared to convectional irrigation (Dry and Loveys 1998; Loveys et al,1998); This irrigation technique has also increased considerably water use efficiency in grapevines by up to 50 percent or more compared to convectional irrigation (Loveys et al., 1997). The PRD technique has been shown to reduce the need for pruning (Dry et al., 1996) due to reduced vigour. Interesting results on the application of PRD on cotton showed that the crops were ready for harvest three weeks earlier than the control treatment (Mingo and Davis, 2001). Dzikiti (2007) observed on average larger fruit size in the PRD treatments, a favourable result in water use efficiency in citrus compared to the convectional practice

Apart from work by Hutton (2009) in the sub-tropical climates and Dzikiti (2007) in the Northern Zimbabwe, very few studies on the potential utility of the PRD irrigation strategy on citrus trees growing in warm arid and semi-arid tropics have been done. This thus makes PRD a new citrus tool to apply in warm arid and semi-arid regions.

However, most of the studies comparing PRD and convectional irrigation applied only half the amount of water in PRD compared to convectional irrigation assuming that PRD was responsible for the observed differences, but ignoring the possible effect of reduced irrigation (Guet, 2004). Thus at present, there is considerable controversy concerning the effects of PRD because physiological and agronomic data are being measured in many fruit crops under PRD in different edaphoclimatic conditions. Recent investigations have reported either no or only subtle differences in citrus and vine water use, crop yield of fruit quality compared to convectional drip irrigation at the same irrigation.

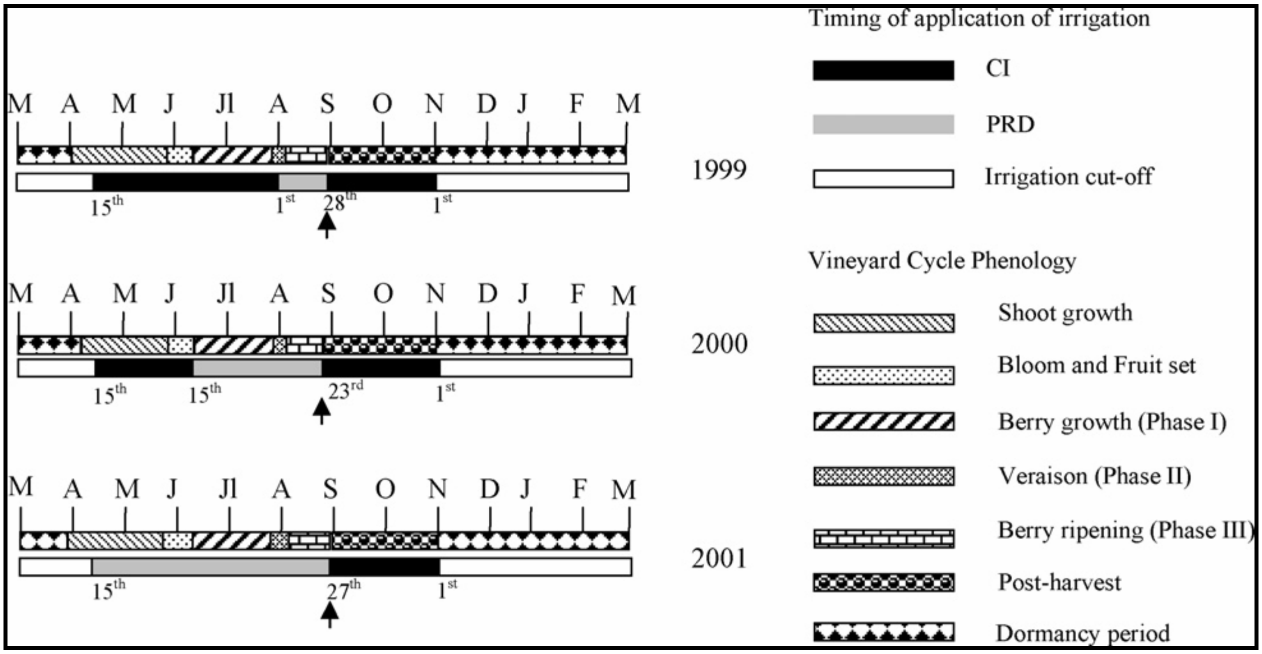

Fig 2.4 Timing of application of PRD during the growing season for each year and orchard cycle phenology. (from De la Hera, 2006)

From fig 2.4, when PRD was applied with half the amount of water as the convectional irrigation in grapevines after veraison (from veraison to harvest) and after fruit set (from fruit set to harvest), there were no significant differences for most yield parameters. The exception was cluster weight; which was significantly higher for PRD vines than for convectional irrigation. However when PRD was applied earlier in the growing season (from budburst to harvest) there were significant differences between irrigation treatments for different yield parameters. The yield of PRD was 3 percent higher.

To make informed decisions, detailed investigations were made on the effects of timing PRD, which applied half the amount of water as the convectional irrigation on citrus trees.

2.9 Measurement of crop water consumption

2.9.1 Stem Heat Balance Sap Flow Sensor

The stem heat balance method requires a steady state and a constant energy input from the heater strip inside the gauge body. Therefore the stem section must be insulated from changes in the environment and for the same reason, the gauge time constant is limited from five minutes to an hour, depending on the flow rate and the stem size. A gauge, fig 2.3 is composed of a heater extended and the stem, surrounded by a thermopile composed of thermo junction on each side of the sheath. Thermo junction pairs, installed on two strips, one just above and another just below the heater, allow the measurement of the temperature differences in the limits of the sampled section of the stem.

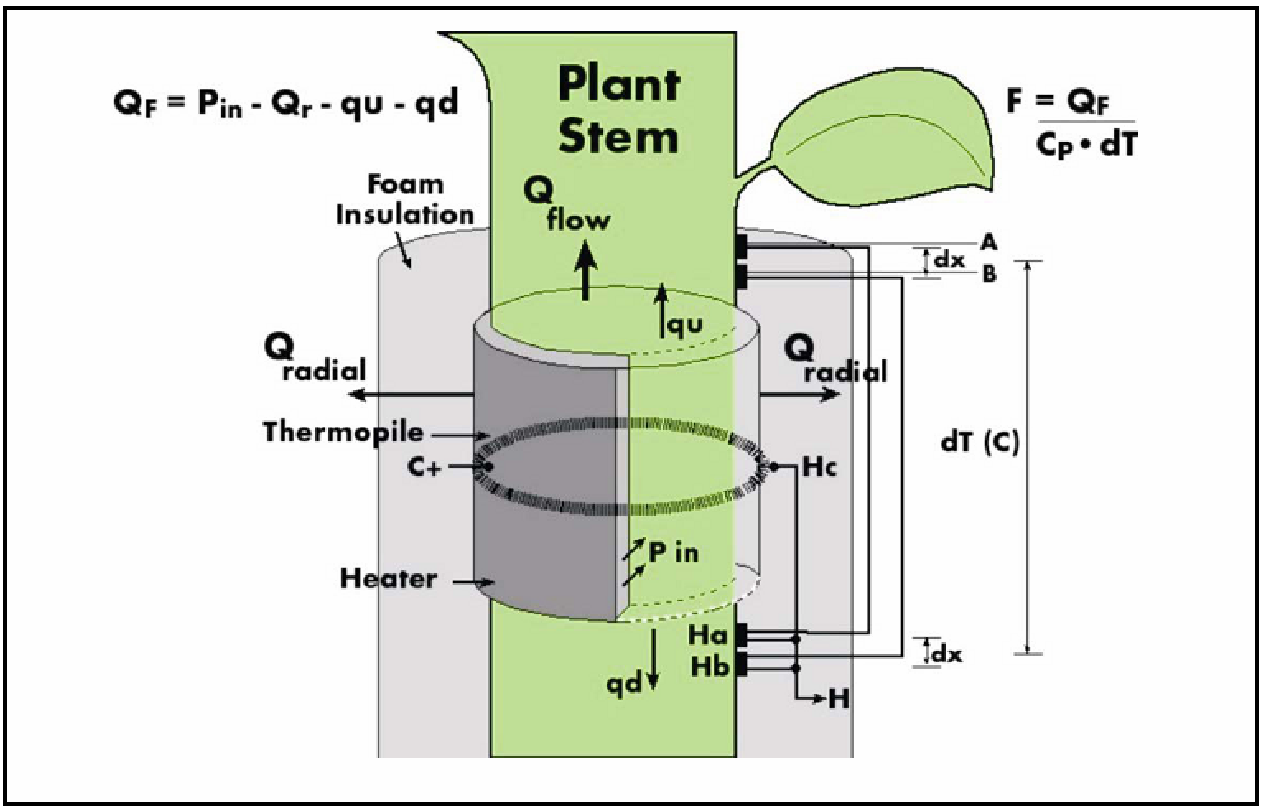

Fig 2.5 A stem section and the possible components of heat flux, assuming no heat storage (van Bavel 1994).

In this technique, a constant power, P_{in} is applied to the plant segment encircled by a small flexible heater, which is a few centimetres in width, wrapped around the organ where sap flow is to be measured (Smith and Allen, 1996). Then energy balance equation for the segment is then solved for the amount of heat take up by the moving sap stream under steady state conditions as shown in fig 2.4. According to Sakuratan (1981) and Baker and van Bavel (1987) the heat balance of the branch can be written as

$$P_{in} = q_v + qr + q_f \qquad \text{.....2.6}$$

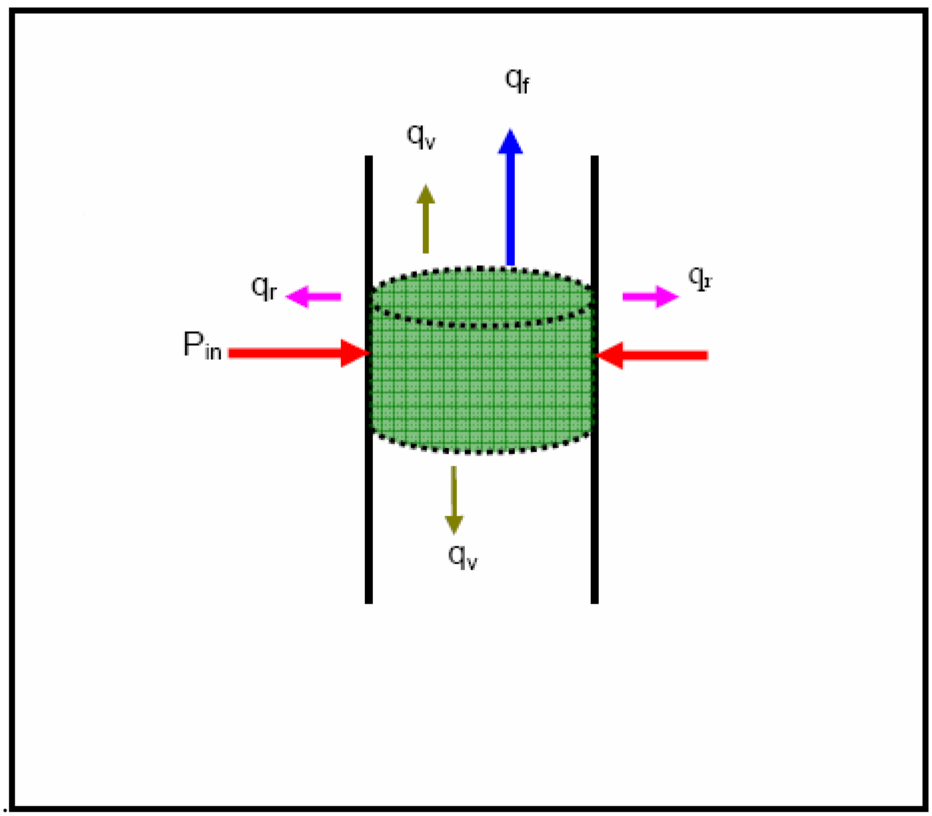

Fig 2.6 Energy balance components of the heat balance sap flow sensor connected to the plant. (Dzikiti, 2007).

Where P_{in} = Power input to plant

q_v = rate of vertical heat loss by conduction

q_r = radial heat loss by conduction

q_f = heat uptake by the moving sap system

By measuring P_{in}, q_v, and q_r , the remainder, q_f can be calculated. q_f is the heat convection carried by the sap. The heat uptake by the moving sap system can be calculated by subtracting q_v and q_r from P_{in}. The heat flux can be converted directly to mass flow rate by dividing by the specific heat capacity of water and the sap temperature increase.

From Ohms law:

$$P_{in} = \frac{V^2}{R} \qquad \text{…..2.7}$$

where V is the supply voltage and R is the heater element impedance.

ΔT_a and ΔT_b are the temperature gradients measured by the axial thermocouples above and below the heater. q_v is calculated as follows

$$q_v = A_{st} K_{st} \left[\frac{\Delta T_b - \Delta T_a}{X} \right] \qquad \text{…..2.8}$$

Where A_{st} = is the cross sectional area of the heated section

K_{st}= the thermal conductivity

X = distance between the two thermocouple junctions.

q_r is then calculated as

$$q_r = K_{sh} \Delta T_r \qquad …..2.9$$

Where K_{sh} = effective thermal conductance of the sheet of materials surrounding the heater, the value s unknown.

ΔTr = is the radial temperature gradient

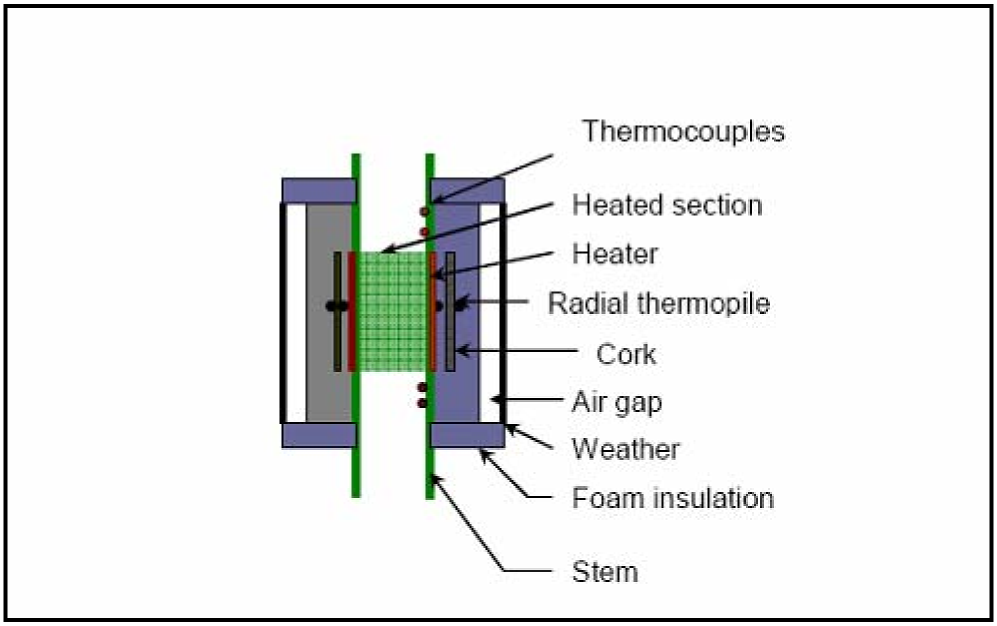

Fig 2.7 Vertical section through the stem heat balance sap flow gauge.(Dzikiti, 2007).

B) Thermal Dissipation Probe

The thermal dissipation probe (TDP) transpiration sensor measures sap velocity which is converted to volumetric flow rate. The TDP has two thermocouple needles inserted in the sapwood, the upper one containing an electric heater. The probe needles measure the temperature difference (dT) between the heated needle and the sapwood ambient temperature below. The dT variable and the maximum dTmax at zero flow provide a direct conversion to sap velocity.

The thermal dissipation technique measures the difference in temperature (dT) between a heated upper needle and a lower reference needle when placed in the sapwood, or conducting xylem of a woody stem. Using a regulated, known voltage, the stem is constantly heated to approximately 8°C above ambient sap. As sap flows past the two needles, the lower reference needle records the ambient sap temperature and the upper heated needle is cooled. If rapid sap flow occurs the difference in temperature between the two needles is low as the heat input from the upper needle is being quickly dissipated.

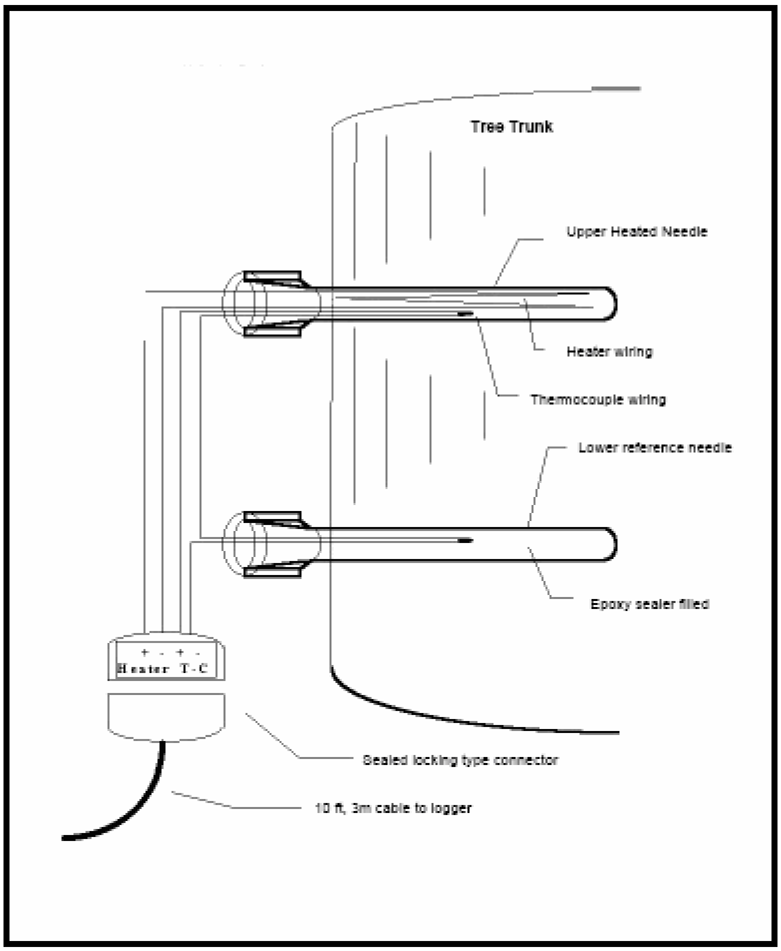

Fig 2.8 Diagram of the thermal dissipation probe (TDP) showing the technical details of the sensor. (Dynamax Inc, 1997).

When sap flow is low or close to zero a maximum difference in temperature or dTmax is recorded because heat is no longer being dissipated from the heated upper needle. The Granier's empirical equation then uses the measured dT and dTmax values to calculate sap velocity. Granier (1987) defined a dimensionless flow index K as

$$K = (dTmax - dT)/dt \quad \text{.....2.10}$$

The sap velocity (V, cm s^{-1}) averaged over the whole length of the needle is related to the variable K according to the empirical equation by Granier (1987) as

$$V = 0.0119K^{1.231} \quad \text{.....2.11}$$

To convert the sap velocity into the mass sap flow rate (F, g h^{-1}), then an estimate of the conducting sapwood area (A_s) is required so that:

$$F = 3600A_sV \quad \text{.....2.12}$$

2.10 Estimating evapotranspiration, ET from Meteorological data

Many methods for estimating ET, based on one or more atmospheric parameters which control ET have been developed (Kang et al., 1996). Air temperature, solar radiation and pan evaporation are the most commonly used parameters. Temperature and relative humidity of air affect the rate of diffusion of molecules while net radiation provides energy for evaporation. Air movement (wind) carries water vapour from the crop surface and maintains gradient water potential from the leaves to adjacent parts of the atmosphere in addition to importing energy from warmer or drier locations (advection). Hence Evapotranspiration can be quantified from weather data using meteorological conditions (Allen et al., 1998).

2.10.1 The Penman Monteith Equation

Penman (1958) combined the energy balance with the mass transfer method to derive an equation, Penman's combination equation. The equation was further developed by Monteith (1981) to form the Penman-Monteith combination equation. The Penman-Monteith combination equation includes resistance factors accounting for aerodynamic and surface vapour flow resistance at soil and leaf surfaces and through leaf stomata, and allows the method to be used when considering cropped surfaces (Blonquist *et al*., 2006).

2.10.2 FAO Penman Monteith Equation

It is now recommended as the sole standard method for the definition and computation of the reference evapotranspiration. The reference evapotranspiration is defined as occurring from a hypothetical reference crop with an assumed height of 0.12 m, canopy resistance of 70 m s^{-1} and an albedo of 0.23 closely resembling evapotranspiration from an extensive surface of green grass of uniform height actively growing and not short of water. Assuming standard meteorological observations at 2 m height the Penman-Monteith equation is written as;

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \qquad \text{.....2.13}$$

Where ETo = reference evapotranspiration

Rn	=	net radiation at the crop surface ($MJm^{-2}day^{-1}$)
G	=	soil heat flux density ($MJm^{-2}day^{-1}$)
T	=	air temperature at 2 m height (^oC)
U_2	=	wind speed at 2 m height (ms^{-1})
e_s	=	saturation vapour pressure (kPa)
e_a	=	actual vapour pressure (kPa)
e_s-e_a	=	saturation vapour pressure deficit (kPa)

Δ = slope vapour pressure curve (kPa $^{o}C^{-1}$)

γ = psychometric constant (kPa $^{o}C^{-1}$)

Using this equation ETo can be calculated from readily available climate data. The FAO Penman Monteith equation has received favourable acceptance over much of the world and has become the most widely used method of estimating evapotranspiration (Cassa et al., 2000). It has shown accurate and consistent performance in both arid and humid climates.

CHAPTER 3

MATERIALS AND METHODS

3.0 Introduction

Water resources in Zimbabwe are limited and regarded as scarce on a global scale. The situation is worsened by population growth and the demands of a vibrant economy. As a result we are compelled to re-evaluate our current strategies of water use. Water, although renewable, is a finite resource that is distributed unevenly both spatial and temporally and through time. Therefore, its use and distribution will become more and more expensive as the demand grows in competing sectors.

For this reason, alternative irrigation methods are required to utilize water optimally while still attaining good quality agricultural products. A relatively minor reduction in irrigation water could substantially increase the water available for other purposes. An increase in agricultural productivity may be dependent on either the availability of more water for irrigation or an increase in the efficiency of water use. Recent results have demonstrated that partial root zone drying (PRD) irrigation techniques can increase the efficiency of water use with many crops (Dry et al., 1996). Loveys et al (2000) showed that for some grape cultivars, partial root zone drying could save water by 50 percent and yet maintain yield.

This study is a follow up on Dzikiti 2007 ‘s work that was carried out in 2005-2006 growing season.

PART A

3.1 Available Data

The data used in this part of the experiment was collected by Dzikiti 2007 in the 2005/2006 growing season.

3.1.1 Sap Flow Measurements

For the data used in this study the leaf transpiration rates were monitored using sap flow gauges. Stem heat balance probe, was used to quantify the water use by individual orange trees. The SGB19 heat balance sap flow gauge (Dynamax Inc. Houston, USA) was installed on the trees in the treatments. Spatial up scaling of the sap flow from single tree to plantation level was done using estimates of the leaf area index of the orchard. Detailed description of the experimental designs and data collection procedures can be found in Dzikiti (2007).

The sap flow rates of the trees in different treatments was then determined and evaluated. These were related to the respective yields obtained in the 2005-2006 growing season.

3.1.2 Yield measurements

The total mass of the fruit was established by picking and weighing all the fruit and average fruit mass per tree was calculated. The yield results were used to compare the treatments effects on yield, of applying partial root zone drying.

3.1.3 Data Analysis

The historical data was used to calculate plant sap flow measurements. These were calculated for every 5 minutes in Excel. Cumulative sap flow rates were then calculated and total sap flow rates per day were observed. These were then used to estimate evapotranspiration. These evapotranspiration rates were then compared with the total yields obtained in the different irrigation regimes.

PART B

3.2 Site description

The study was carried out at Mazowe Citrus Estate (MCE), (17.46°S, 31.00°E, 1189 m a.s.l).Navel orange [*Citrus sinensis* (L) Osbeck] trees budded on Troyer citrange rootstock [*Citrus sinensis**Poncirus trifoliate* Raf.] in an orchard of 8.6 Ha under drip irrigation were chosen. The trees were planted in 2001 and were 8 years old by the time the study was carried out. The orchard is situated on a gentle sloping terrain about 40 km to the north of Harare, predominated by deep clayey soils whose physical properties are summarized by Hussein 1982 as shown in the table 3.1

Table 3.1 Characteristics of the soil at Mazowe Citrus Estate, Zimbabwe (from Hussein, 1982).

Soil Properties	Top Soil	Sub soil
Sample Depth (mm)	0-150	600-750
Clay %	63	81
pH ($CaCl_2$)	6.6	5.7
Bases exchange (me %)	27.5	15.9
Cation exchange (me %)	33.2	18.1
E/C value (%)	53	22
S/C value (%)	44	20
Bulk Density (kgm^{-3})	1330	1350
Available water capacity (mm/100mm)	14.9	14.3

The soil is dark red in colour with a high clay percentage. The trees were planted in rows and tree spacing was approximately 2.75 m x 6 m. The trees were planted on ridges approximately10-15 cm high to facilitate the drainage of excess water from the root zone especially during the rainy season. The trees were drip irrigated using 15 mm polypropylene dripper lines with pressure compensated button emitters were spaced at 0.30 m along the drip lines. The emitter rate is 1.7l/ha. According to the local citrus grower's practice, all the trees were watered using a single drip line running close to the main stem of the trees.

Fig 3.1 Experimental Orchard at Mazowe Citrus Estate facing an approximate EW direction.

3.3 Meteorological Measurements in 2009/2010 season.

The microclimate in 2009/2010 season was monitored using an automatic weather station located to the south west of the orchard approximately 15 m from the edge.

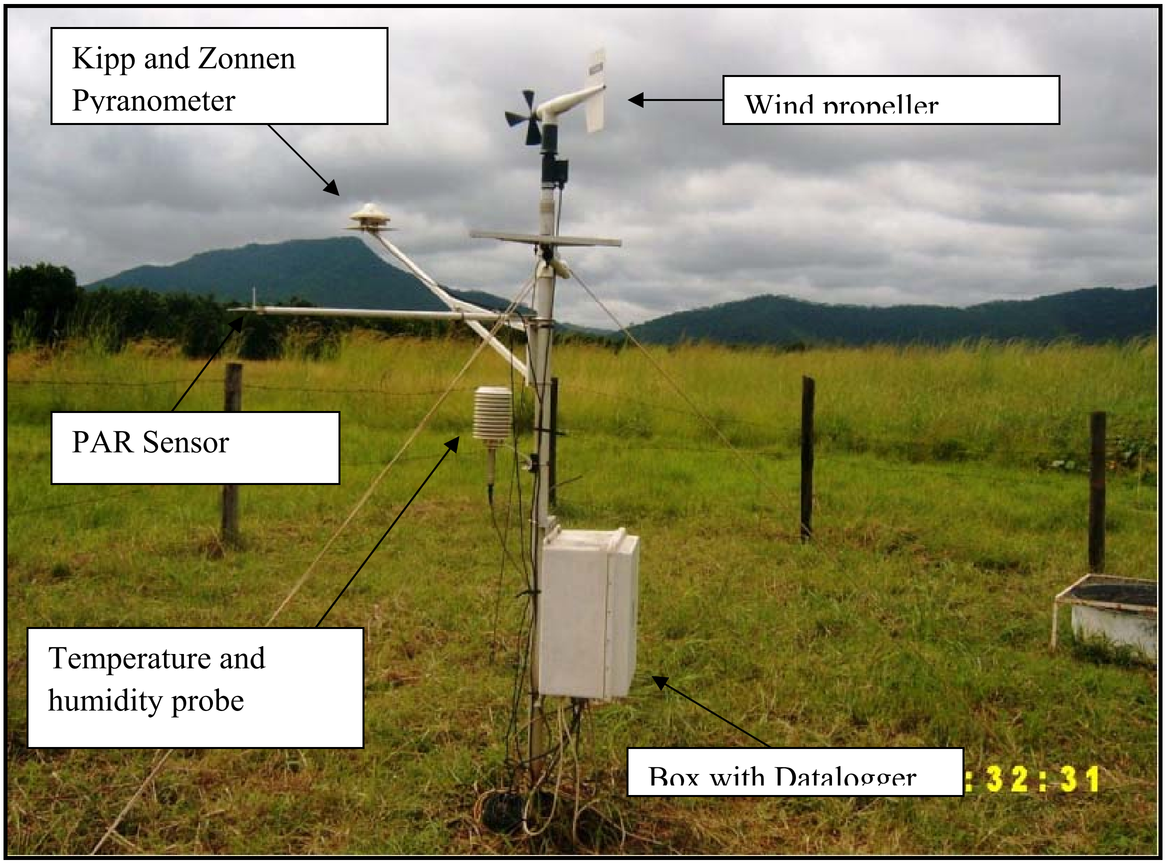

Fig 3.2 Automatic weather station to monitor the orchard microclimate at the trial site at Mazowe Citrus Estate, Zimbabwe.

Wind speed was monitored using an AL100 cup anemometer, (Vector Instruments, Rhyl, UK) at 2 m height. Air temperature and humidity were monitored using an HMP35AC probe inserted in a 12-plate Gill radiation shield (Vaisala Ltd, Finland) at approximately 1.5 m above the ground. Signals from all sensors were recorded automatically on a data logger (CR23X, Campbell Scientific Ltd, Shepshed, UK).

3.4 Experimental Design

The experiment was designed as a randomized complete block with two replications. The treatments comprised of six different irrigation regimes. Each treatment was allocated to each row randomly using random numbers generated by Genstat.

3.4.1 Treatments

The 6 irrigation treatments were established in October 2009. Each treatment comprised of one single row with ten trees each. The ten trees were selected such that the outermost rows were excluded to eliminate edge effects. The treatments were replicated once such that each treatment will have two rows. The effects of the different PRD treatments were evaluated against the current practice and the control.

Before the treatments were established, all the citrus trees were being irrigated according to the grower's practice. The grower's practice is whereby all the trees in the orchard were watered using a single drip line running close to the main stem. It is assumed to replace 100% of the crop evapotranspiration. During the 2009/2010 season the trees were subjected to an irrigation cycle that changed the daily duration of each irrigation event. It was depended on the growth stage of the fruit as shown in Table 3.2.

Table 3.2 Typical schedule for the eight year old Navel orange trees at Mazowe Citrus Estate, Zimbabwe during the 2009/2010 season.

Month	Duration of irrigation (h)	Fruit growth stage
June-July	6	Before spring flush
August-December	8	Flowering/fruit set
January-March	-	Fruit growth/cell expansion
April-May	~3	Maturation

During the flowering and fruit set phases, which are the crucial growth stages, longer irrigation durations were implemented. During summer, irrigation was applied to supplement rainfall and that is after fruit set. Shorter durations were used at maturation to improve the internal quality of the fruit.

Fig 3.3 The current grower's practice using one drip line next to the row of trees. The control treatment also has one drip line.

When one drip line is being used for irrigation, soil moisture will be concentrated on one side of the root zone as shown in fig 3.4. During the whole growing season, in the current grower's practice and in the control treatments, only one side of the root zone was wet, the other side was dry.

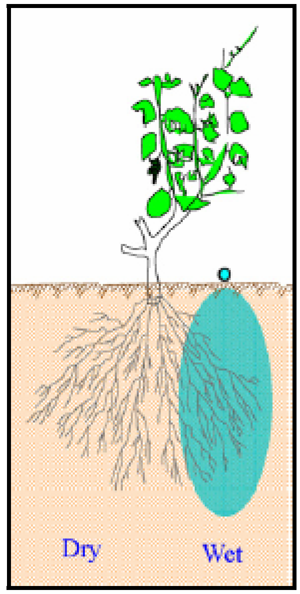

Fig 3.4 Only one side of the root zone will be wet during the whole season because one drip line was used in the control and in the growers practice (from Du 2006).

There are six treatments, which are

1) Control: One drip line, one side of the tree irrigated according to ETo data from the automatic weather station.

2) Current practice: Single drip line, scheduled according to grower.

3) PRD 2 drip lines applying half of control

4) Control at flowering or fruit set and PRD 50% at stage 2.

5) Control at flowering or fruit set and PRD 50% at stage 3.

6) Control at flowering or fruit set and PRD 75% at stage 2 and PRD 50% at stage 3.

The control treatment was also irrigated by a single drip line. One side of the tree was irrigated using potential evapotranspiration data from the automatic weather station and soil measurements.

The third treatment was the partial root zone drying treatment. This comprised two drip lines, one either side of the row. Irrigation was done using one line at a time but the wet zones alternated every ten days. Half the volume of water was delivered in this treatment as in the control treatment. The fourth treatment was a partial root zone drying treatment also. In this treatment, the control treatment was introduced at the flowering and fruit set stage of development of the trees where one drip line was used to irrigate. Then at stage two of development, partial root zone drying was introduced and this was scheduled to deliver 50% of the water.

The fifth treatment the control was used up to stage three where partial root zone drying was introduced. This was also scheduled to deliver 50% of the water. In the sixth treatment, the control was used at flowering and fruit set and at stage two, partial root zone drying was introduced and was delivering 75% of the water. At stage three it was reduced to 50%. Random sampling of the treatments was done using random numbers generated by Genstat. The table 3.3 shows the layout of the treatments.

When two drip lines were used in the PRD treatments, the wet and the dry sides of the root zone were alternated as shown in fig 3.5.

Fig 3.5 The partial root zone drying treatments with two drip lines. Irrigation was done using one drip line at a time and switched at 10 day intervals.

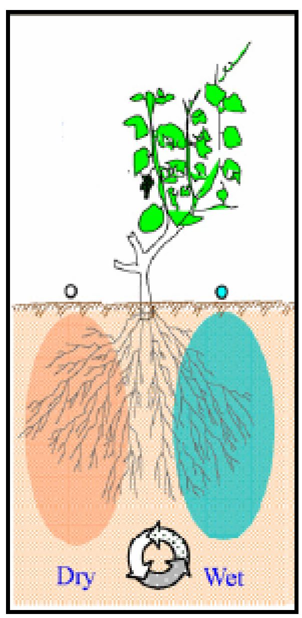

Fig 3.6 For the PRD treatments, two root zones of the citrus trees were alternately irrigated during the consecutive irrigation (from Du 2006).

Table 3.3 Layout of the treatments in the field. The rows 8,9,15 and 16 are outside the scope of this experiment.

Row	Treatment	Replication
3	Control at flowering or fruit set and PRD 75% at stage 2 and PRD 50% at stage 3.	**1**
4	Control at flowering or fruit set and PRD 50% at stage 2	
5	Control: One drip line, one side of tree irrigate according to ET_o data from the automatic weather station.	
6	Control at flowering or fruit set and PRD 50% at stage 3	
7	Current grower's practice: Single drip line, scheduled according to grower.	
10	PRD: 2 drip lines applying half of the control.	
11	Control at flowering or fruit set and PRD 50% at stage 2	**2**
12	Control: One drip line, one side of tree irrigate according to ET_o data from the automatic weather station.	
13	Control at flowering or fruit set and PRD 50% at stage 3	
14	PRD: 2 drip lines applying half of the control.	
17	Control at flowering or fruit set and PRD 75% at stage 2 and PRD 50% at stage 3.	
18	Current grower's practice: Single drip line, scheduled according to grower.	

3.4.2 Determination of the irrigation duration

The duration of irrigation regimes was calculated from October 2009 to February 2010 using drip line specifications, orchard characteristics and the evaporative demand of the atmosphere. Given that the drip lines were 15 mm polypropylene with pressure compensated button emitters with an emitter rate of 1.7 l/ha and an emitter spacing of 0.3 m. Tree spacing in the orchard is 2.75 m in each row and 6 m inter-row spacing.

The potential evapotranspiration, ETo data of the same site from the past studies was used. A daily average ETo value of 3.38 mm for January was used. A daily K_c value of 0.7 was used (Dzikiti, 2007) since there is a small variation in the extend of vegetation cover throughout the year in citrus as it is an ever green plant (Allen et al., 2004). So for the month of January 2010 for example, the mean daily crop evapotranspiration, ET_c, was calculated as follows

$$ET_c = ET_o * K_c \qquad \text{....3.1}$$

$$= 3.83*0.7$$

$$= 2.68 \text{ mmday}^{-1}$$

Where ETc = mean daily crop evapotranspiration

ET_o = potential evapotranspiration

K_c = crop coefficient

Considering a hypothetical one hectare area o f the orchard with simplified dimensions of 100m* 100 m, the total number of emitters per hectare (n) was determined by

$$n = \frac{100}{0.3} * \frac{100}{6} \qquad \text{.....3.2}$$

= 5556 emitters

From Dzikiti (2007), the fraction of the orchard that is irrigated can be estimated by considering the region between four emitters in the neighbouring tree rows. The wetted region around each emitter is approximately elliptical extending for approximately 1.0 m along the major axis of the ellipse at right angles to the drip line and 0.375 m along the minor axis parallel to the drip line.

The wetted fraction of the soil = $\frac{\pi * 0.375 * 10}{6 * 0.3}$ …..3.3

= 0.65

The total volume of water, Vw applied per hectare in litres is

V_w = X*ER*n …..3.4

Where V_w = total volume of water applied per hectare

x = number of hours or duration of the irrigation event

n = total number of emitters per hectare

ER = rate of emission of water by the drippers

Therefore Vw = X*1.7*5555.55

=9444.435X

The irrigation depth can be calculated from

Irrigation depth = $\frac{Vw}{10000 * 0.65}$ …..3.5

From equation 3.6 $\quad 2.68 = \dfrac{Vw}{10000 * 0.65}$ …..3.6

Where, $\quad V_w = 17420$ litres

So $\quad V_w = 9444.435X$ …..3.7

To get the duration X, we substitute

$$X = \frac{Vw}{9444.435} \quad \text{…..3.8}$$

So the duration for the control is 1.844 hours

Table 3.4 The irrigation durations for the month of January.

Row	Treatment	Duration (hrs)
3	Control at flowering or fruit set and PRD 75% at stage 2 and PRD 50% at stage 3.	0.9
4	Control at flowering or fruit set and PRD 50% at stage 2	0.9
5	Control: One drip line, one side of tree irrigate according to ET_o data from the automatic weather station.	1.8
6	Control at flowering or fruit set and PRD 50% at stage 3	0.9
7	Current grower's practice: Single drip line, scheduled according to grower.	3
10	PRD: 2 drip lines applying half of the control.	0.9
11	Control at flowering or fruit set and PRD 50% at stage 2	0.9
12	Control: One drip line, one side of tree irrigate according to ET_o data from the automatic weather station.	1.8
13	Control at flowering or fruit set and PRD 50% at stage 3	0.9
14	PRD: 2 drip lines applying half of the control.	0.9
17	Control at flowering or fruit set and PRD 75% at stage 2 and PRD 50% at stage 3.	0.9
18	Current grower's practice: Single drip line, scheduled according to grower.	3

3.5. Total Water Use Calculation

3.5.1Calculating water used by each treatment per hectare

The total amount of water used by each treatment was calculated using the emitter rate and the duration of the irrigation event over the total number of days that each irrigation event was run in each month. Assuming no clogging each emitter released 1.7 litres of water in one hour, and this is the emitter rate. From section 3.4.2 above the total number of emitters per hectare is 5555.So for each treatment to get the total amount of water used per hectare, thus

Total water used = Emitter rate*duration of irrigation/month*number of emitters/ha …....3.9

This gives the total amount of water that would be applied by each treatment, considering the fact that the treatment would have been applied in a one hectare area.

For example in the month of October, there were 25 days of irrigation. For the control treatment, a total of three hours per day was calculated and used. So, for each emitter, after three hours of irrigation the amount of water released was 5.1 litres a day. Multiplied by the number of days, which is 25, each emitter delivers 127.5 litres of water per month. For the 5555.55 emitters found in a hectare, thus

Amount/hectare = 127.5litres*5555.55 emitters …….3.10

= 708332.625 litres

Calculations were made for all the treatments in all the months that were irrigated.

3.6 Water Use Efficiency Determination

Water use efficiency (WUE, kg/m^{-3}) in this study was defined as the ratio of the amount of yield obtained per amount of water applied to the crop. The total yield obtained of each treatment was divided by the total amount of water applied in each treatment (irrigation + rainfall). This was calculated as:

$$WUE = \frac{Y}{W} \qquad \text{….. .3.11}$$

Where Y = yield (kg/ tree), W = total water supplied to the crop (irrigation + rainfall).

3.7 Fruit growth measurements

During the 2009/10 fruit growing season, fruit growth rate was monitored. Fruit diameter was monitored after every ten days using a 0.05 mm accurate pair of hand-held Venier callipers as shown in fig 3.5.

Fig 3.7 Hand held pair of venier callipers, monitoring the growth rate of a fruit of a 8 year-old Navel orange tree in the Mazowe Citrus Estate, Zimbabwe.

On two trees in each treatment there were 10 tagged fruits per tree with an equal number of fruit on the eastern and western side of the canopy. There were two mutually perpendicular measurements were taken along the equator of each tagged fruit and an average diameter value was calculated to reduce errors.10 fruits were also tagged on two trees in each of the treatments to monitor fruit abscission. The number of tagged fruits remaining on the tree was counted. Fig 3.6 shows the way the fruits were tagged.

Fig 3.8 A tagged fruit in one of the treatments in the experiment at Mazowe Citrus Estate

3.8 Fruit Yield Measurements

Harvesting was done on the 9th of April 2010. In each row two trees were randomly chosen to investigate the yield components. This was done using random numbers generated by Excel. The total mass of all the fruit was established by picking all the fruit and then weighing, and then the average fruit mass per tree was calculated. In addition the total number of fruit per tree was counted and an average number of the fruits per tree were calculated.

3.8.1 Crop Load

Fruit size is very important in determining marketable yield. Crop load affects fruit size, with heavy crops resulting in smaller fruit. However, the number of fruit per tree that would give both optimal yield and fruit size is difficult to predict. Crop load, which is the number of fruit per cm^2

was calculated after measuring the stem diameters of the trees which were harvested in each treatment. Using the relationship from Dzikiti (2007), the total leaf area can be obtained from

$$Y=13420x^{2.3988} \qquad \ldots\ldots 3.12$$

Where Y = leaf area (m^2)

x = the stem diameter below the first branch point

Using the stem diameters of the trees that were harvested the total leaf area of representative tree was calculated

3.9 Fruit Quality Analysis

This experiment was done to determine the effects of timing of partial root zone drying (PRD), in fruit quality. Internal quality aspects were considered. Fruit juice quality was determined at Mazowe Citrus Estate laboratory according to methods approved by the Mazowe Citrus Estate quality tests. Six different samples were considered for this experiment. A sample of 12 fruits per treatment was taken, six fruits from the eastern side of the tree and six fruits from the western side of the tree. These were weighed and each fruit was cut into along the equator to extract juice. The peels were weighed after the extraction of juice to get the juice percentage. The extracted juice was then further tested for percentage juice, percentage, total soluble solids, percentage total acidity and the total soluble solids: total acidity ratio, (TSS: TA).

3.9.1 Percentage juice

The mass of the fruit in each sample was determined by weighing on a scale graduated in 1 g units. All the fruits in each sample were cut into halves at the equator. The juice was pressed out using a Sunkist hand reamer and collected into a 1 litre jug. The juice was then filtered through a parachute cloth into another jug. The remaining fruit residue (pulp) was squeezed to extract as much juice as possible. The residue together with the peel was then weighed. Juice percentage was calculated to 0.1% as:

$$Juice\% = \left[\frac{(W_G - W_P)}{W_G} \right] * 100 \qquad .....3.13$$

Where W_G is the weight of the whole fruit sample and W_P is the weight of the peel and pulp.

3.9.2 Percentage total soluble solids (TSS)

The juice extracted from the fruit was allowed to stand for 30 minutes to allow air bubbles to settle. The percentage of sugars (TSS) in the juice is determined by the Brix test. A Brix hydrometer with a range of 6-12% total soluble solids was floated in the extracted juice for three minutes. The hydrometer was read and 0.2 was added to the read value for the height of the meniscus. So

TSS% = Brix reading to the top of the meniscus + 0.2 .....3.14

3.9.3 Percentage total acids

In this experiment, the percentage of the anhydrous citric acid that is in the juice was also determined. 10 ml of the extracted juice was put in a flask and five drops of phenolphthalein indicator were added to the flask. This was placed on a white tile. This was titrated with a normal sodium hydroxide (NaOH). The contents were constantly being mixed and the end point of the titration was a pink colour. The process was repeated and the two readings averaged. Percentage TA was calculated as:

TA% = (Amount of NaOH used in titration) / (Amount of juice titrated) 3.15

3.9.4 Total soluble solids to Total acid ratio

The values of total soluble solids are then divided by total acid to get the ratio. Thus

TSS: TA = TSS%/TA% 3.16

3.10 Data Analysis

The data from the data loggers were collected using a laptop computer with PC208W software and stored as data files and then downloaded to excel for processing and analysis PC208W is computer software that facilitates communication with a CR23X data logger (Campbell Scientific, Logan, UK).

Statistical analysis of yield data was done by means of Analysis of variance (ANOVA).The results were said to be significant if the probability of obtaining this result or a more extreme one when the hypothesis being tested was true was less than 0.05.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.0 INTRODUCTION

This chapter is divided into two parts. The first part discusses the effects of partial root zone drying treatments to transpiration rates and yield of citrus trees. Observed were total daily transpiration rates of the citrus trees over a period of seven days, and the corresponding yields obtained under the three different treatments. It shows how the citrus trees transpire in PRD and non PRD treatments. In Part B of the experiment, partial root zone drying treatments were introduced at different stages of growth of citrus trees to investigate the potential benefits that come with the timing partial root zone drying to the citrus trees. Total water used in the treatments, fruit growth rates, fruit drop, fruit yield, fruit quality and water use efficiency of all the treatments were observed.

PART A

4.1 Response of navel citrus to PRD

Fig 4.1 shows the treatment and climatic variables' effects on the sap flow rates measured at Mazowe Citrus Estate over a period of seven days from DOY 135 to DOY 141 of 2006. The different irrigation regimes had a significant effect on the transpiration rates. The control and the PRD 100% had relatively higher transpiration rates while the PRD 50% had lower transpiration rates, this could have been caused by the fact that, if the plant has excess water it has a tendency of losing more water through high transpiration rates. At the same time the trees that transpired less water had higher yields. In other studies, Du (2006) reported that PRD is associated with a reduction in the amount of irrigation water applied to crops. The difference in transpiration rates become larger when the amount of irrigation water applied to the crop is reduced. This tally with what was observed in the sap flow measurements.

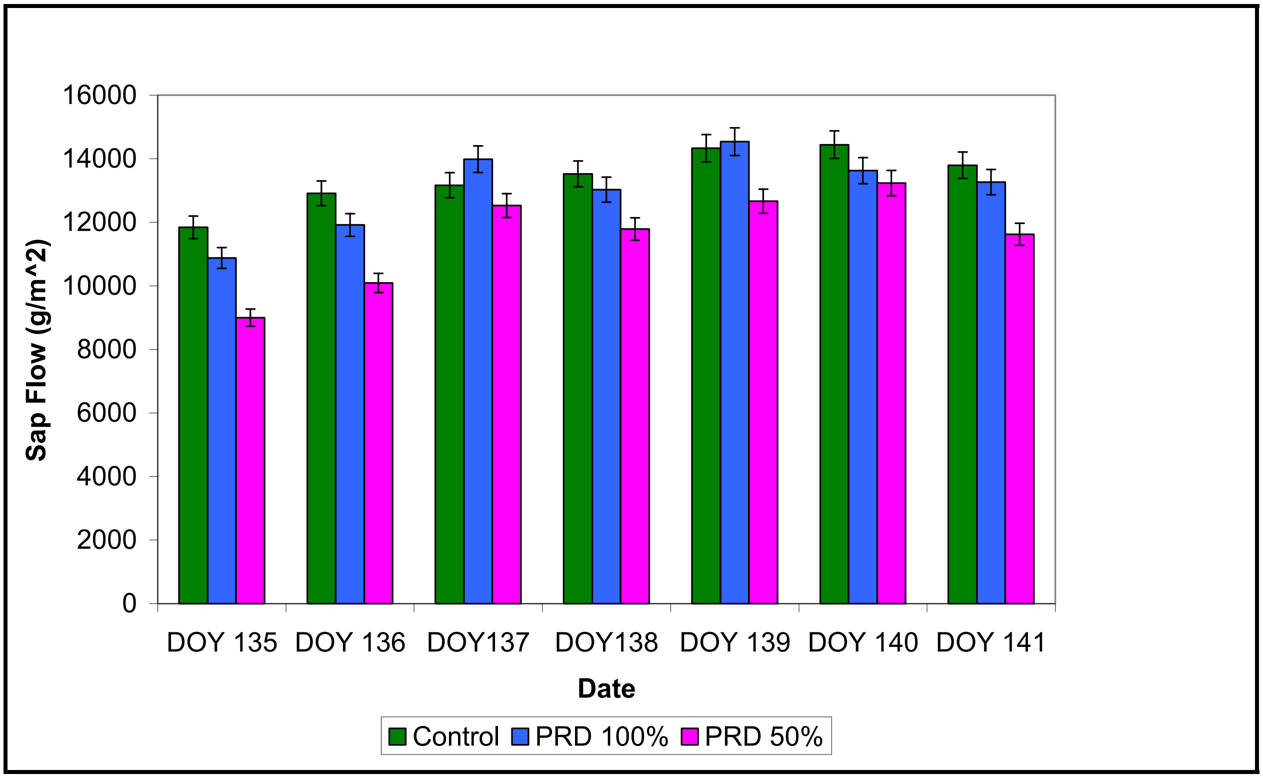

Fig 4.1 Daily total sap flow rates for the control treatment, partial root zone drying 100% treatment and root zone drying 50% treatment during the 2005-2006 growing season as estimated from the heat balance sap flow gauges. (Adapted from Dzikiti 2007)

This shows that the PRD 50% treatment transpires less water because less water was applied to the trees in the treatments. The PRD100% treatment had lower sap flow rates as compared to the control.

Table 4.1 Total yields per tree for the different treatments in the 2005/2006 growing season (from Dzikiti, 2007).

Treatment	Average yield(± 0.1 kg/tree)
Control	28.8
PRD 100%	34.2
PRD 50%	42.3

From table 4.1, the PRD 50% treatment has the highest yield but the total amount of water that was applied was half that of the PRD 100% and control. This shows that when water is applied using the partial root zone drying technique, it will be used efficiently and that yields are not reduced. So, if partial root zone drying saves water without reducing the final yield, then how about timing the technique? That is identifying the stage of development of the citrus trees when the partial root zone drying technique can be introduced to give better yield.

PART B

4.2 Climatology of the trial site in 2009/2010 growing season

Table 4.2 presents a summary of the prevailing climate at the trial site during the 2009/2010 growing season. Warm temperatures characterised the entire growing season as well with an average of around 22^{o}C. A peak temperature of approximately 33.3^{o}C was reached in mid October during fruit set. The average daily potential evapotranspiration was 3.6mm per day.

Table 4.2 The annual variation of the key climatic variables at the trial site at the Mazowe Citrus Estate, Zimbabwe during the 2009/2010 season.

Year	Month	Solar radiation (MJm^{-2})	T_{mean} (^oC)	Mean RH (%)	ET_o(mm day^{-2})	Mean Rainfall (mm)
2009	October	457.8	20.1	59.4	4.9	5.0
2009	November	502.0	20.9	66.5	4.1	73.0
2009	December	601.6	23.6	70.7	3.8	248.5
2010	January	638.0	21.5	83.2	3.6	302.1
2010	February	607.0	21.6	84.3	4.3	154.5
2010	March	603.0	21.3	84.5	4.4	95.5
2010	April	608.5	20.2	81.6	4.0	24.0

4.2.1 Rainfall

Figure 4.2 presents the distribution of 10-daily rainfall received at the experimental site over the 2009/2010 rainfall season. A total amount of 903mm of rainfall was received during the 2009/2010 growing season.. Some dekads of the season had very little or no rainfall while some received substantial amounts. The most wet dekad was the third dekad of January with 181.5mm of rainfall. The most dry dekad was the first dekad of April with 0 mm of rainfall.

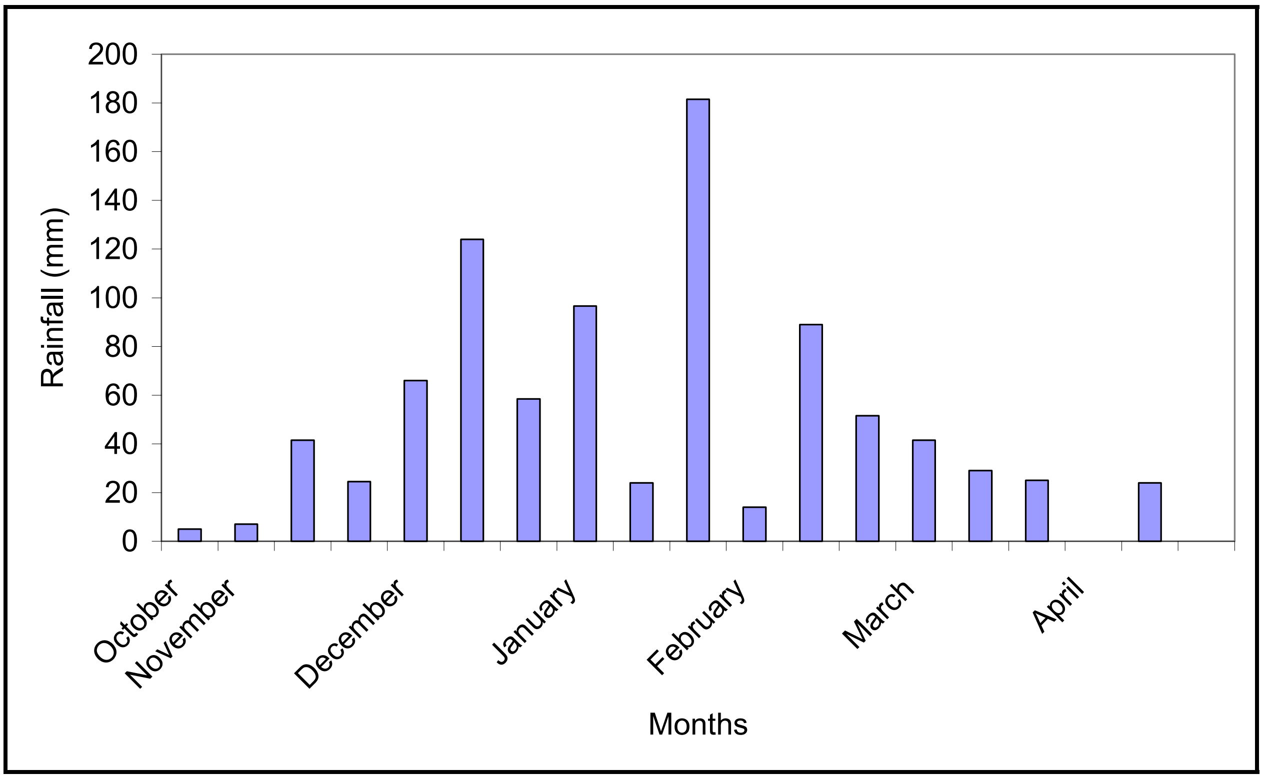

Fig 4.2 Dekadal observed rainfall during the growing season (October2009 to April 2010)

4.4 The rainfall distribution in the 2009/2010 growing season

The rainfall observations indicated poor rainfall distribution, which often characterizes areas in semi-arid regions. The growing season had a total of 902 mm which is very normal, because the area receives on average 750 to 1000 mm per annum (Vincent and Thomas, 1961). In December alone a total of 248.5 mm of rainfall was received which is nearly one third of the total amount received. More than half of the total rainfall received was observed in December and January which gave a total of 550.6 mm. Most of the rainfall was concentrated in the two months and in the third dekad of January that was the most wet dekad. This poor distribution affects the effectiveness of the treatments to some extent, because since the irrigation practice was being done during the summer season, irrigation water would not be used all the times because of rainfall availability.

4.5 Average daily ETo values observed during the growing season

The ETo values show the evaporative demand of the atmosphere during the 2009/2010 growing season. The reference evapotranspiration was calculated using the FAO Penman Monteith Equation (§2.10.2). Meteorological parameters of temperature, relative humidity, wind speed and solar radiation required to calculate ETo were recorded daily on site by means of an automatic weather station. The data logger was programmed to calculate the ETo using the Penman Monteith Equation. In October, the atmosphere had a higher affinity for water; this means there was low humidity. As the season progressed into November the vapour pressure deficit was now decreasing. This was due to the increase in relative humidity because of the rainfall that was now being received. The decreasing trend continued through December up to January. January had the lowest ETo value.

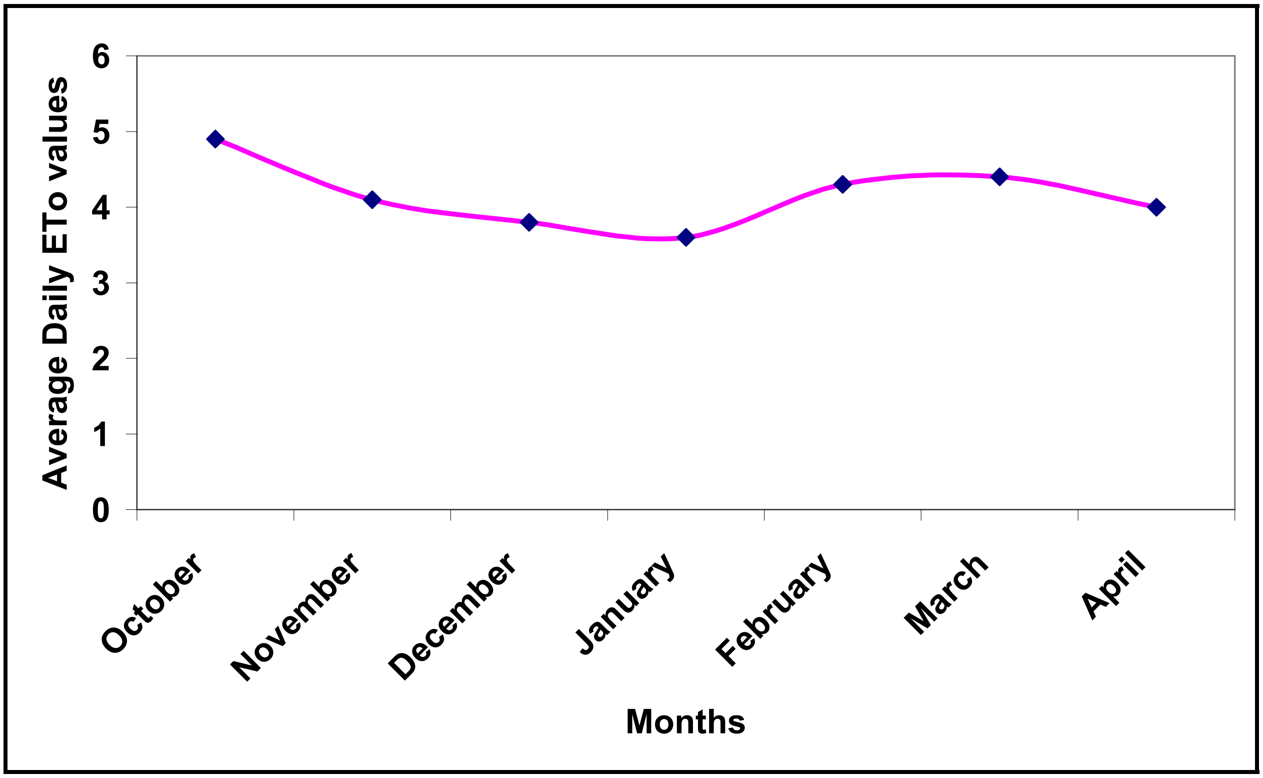

Fig 4.3 Average daily ET_o values observed during the growing season from October 2009 to April 2010.

This was because that was the month that received most rainfall during the growing season. The sharp increase from January to February was because of the dry spell that was experienced in the first dekad of February. From February to March the evaporative demand was almost the same, then it started decreasing form March to April. This was mainly because of the high relative humidity that was caused by high rainfalls experienced in April.

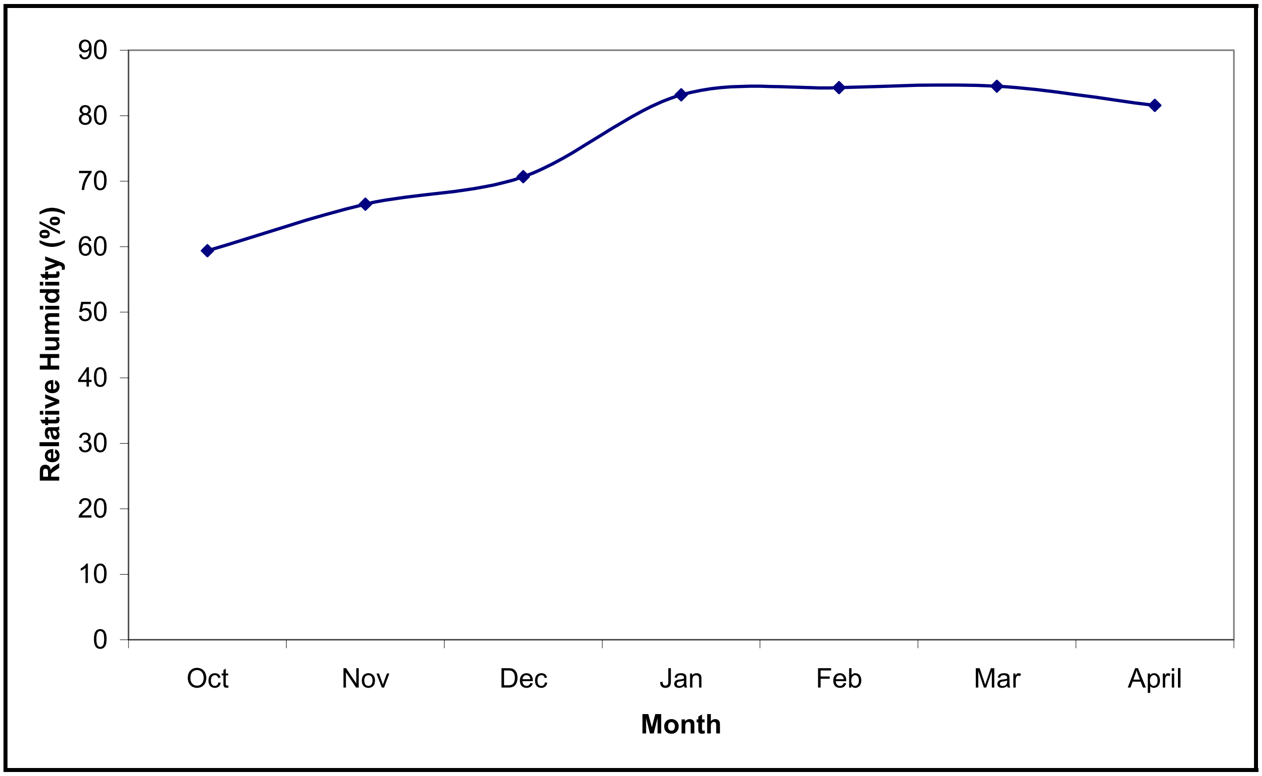

Fig 4.4 The relative humidity values observed during the growing season from October 2009 to April 2010.

The relative humidity (RH) values shown in fig 4.4 correspond to the rainfall received during the whole season. When rainfall received in the season was high, there was higher relative humidity. The RH increase in the month of January corresponds to an increase in rainfall in that month and also that it was the month which the site received the most rainfall.

Fig 4.5 then shows the mean air temperatures experienced during the whole growing season at Mazowe Citrus Estate. In December there was the highest mean ambient temperature. This is following the normal temperature ranges in the semi arid regions were temperatures increase up until December and then start to decline from December.

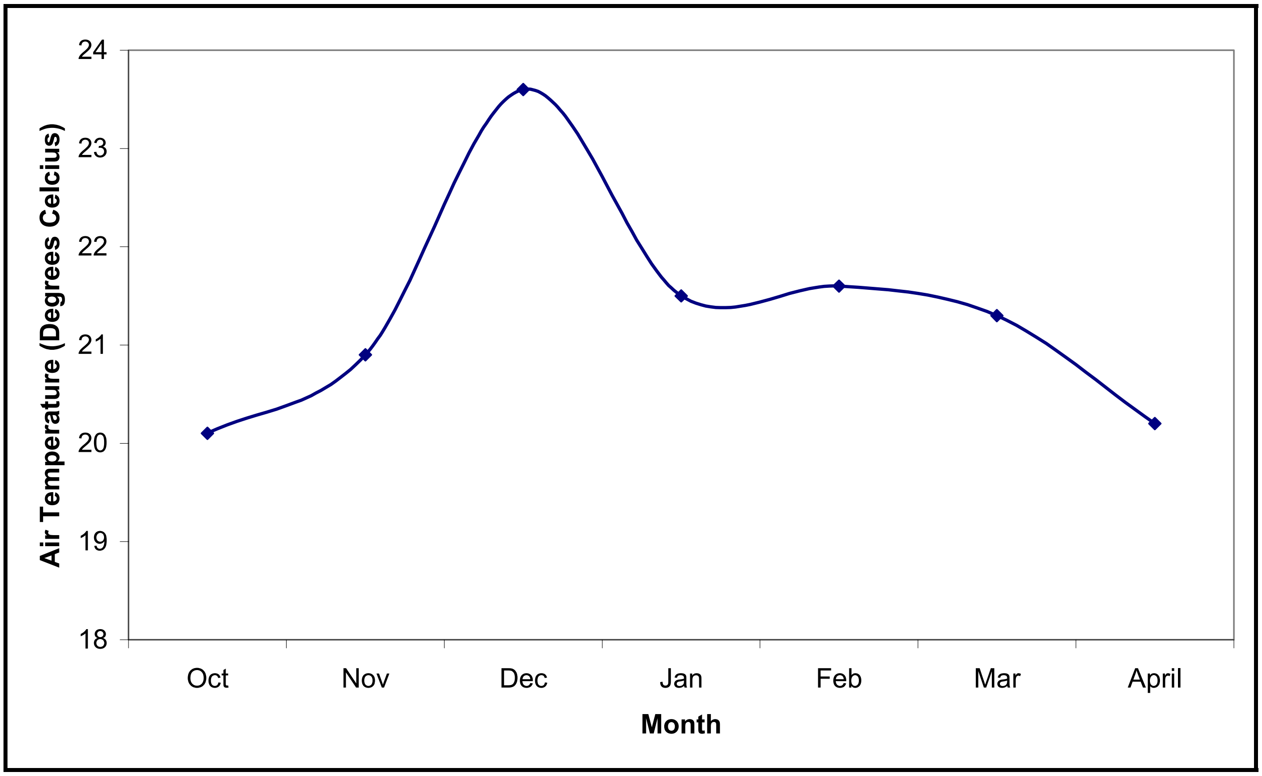

Fig 4.5 The mean air temperatures during the whole growing season at Mazowe Citrus Estate.

4.6 Irrigation durations and total water used in the whole season

The current grower's practice had the highest number of hours of irrigation duration. It had a total of 488 hours of irrigation the whole season. Compared to the control and PRD 50% stage 3 which had 253 and 248 hours respectively the current grower's practice had higher hours of irrigation. PRD 75%, stage 2, 50% stage 3 had 236 hours and 217 hours were for the PRD 50% stage 2. The PRD, half control had the lowest number of hours during the whole season which was 126 hours.

Table 4.3 The total irrigation **durations per treatment for the 2009/2010 season.**

Treatment	Treatment	Total Duration in Hours per month			
		Oct	Nov	Dec	Jan
Control	1	90	90	55	18
Current Practice	2	240	150	78	20
PRD, half control	3	45	45	27	9
Control, PRD 50% stage 2	4	90	90	27	10
Control, PRD 50% stage 3	5	90	90	55	9
Control, PRD 75% stage 2,50% stage3	6	90	90	42	14

These hours led to the amount in litres of water that was used by each treatment. During the whole season the treatments used different amounts of water. The table 4.7 shows the amount of water applied by each treatment. These combined the whole season; table 4.8 shows the amount in Mega litres of water used by each treatment.

Table 4.4 Total water used in the different months by each treatment per hectare in ML.

Treatment		Oct	Nov	Dec	Jan
Control	**1**	0.85	0.85	0.52	0.17
Current Practice	**2**	2.30	1.42	0.74	0.19
PRD, half control	**3**	0.42	0.43	0.26	0.09
Control, PRD 50% stage 2	**4**	0.85	0.85	0.26	0.09
Control, PRD 50% stage 3	**5**	0.85	0.85	0.52	0.08
Control, PRD 75% stage 2,50% stage3	**6**	0.85	0.85	0.39	0.13

Table 4.5 Total irrigation water used in the season by each treatment per hectare.

Treatment	Volume of Water(ML)/ha
Control	2.4
Current Practice	4.6
PRD, half control	1.2
Control, PRD 50% stage 2	2.1
Control, PRD 50% stage 3	2.3
Control, PRD 75% stage2,50% stage3	2.2

The current practice had the highest amount of water that was applied to it because of the higher number of hours that were irrigated in October and November. MCE applied irrigation waster for eight hours in these two months. Then in December, irrigation time was reduced to five hours and then to three hours in January. This is the current practice. The control followed after the current practice and irrigation was scheduled according to historical ETo data of the Mazowe Citrus Estate. The PRD treatment had half of the control and had the least amount of water applied to it. The remaining three other treatments had values of water applied to them which was less than the control because of the changes of water applied at different stages of growth, that is stage 2 and stage 3.

4.7 Fruit Growth

Fruit growth was measured from the early stages of development on all the six treatments. Fruit sizes are indicative of growth patterns. When the first measurements were taken, about 35 days after fruit set, the mean fruit size was similar. Table 4.6 shows the average fruit diameters, at different dates during the growing season for all the fruit tree rows. This involved the two replicates.

Table 4.6 Average fruit diameters in cm for each treatment.

Treatment	DOY 348(2009)	DOY 361 (2009)	DOY 3 (2010)	DOY 13 (2010)	DOY 23 (2010)	DOY 33 (2010)	DOY 43 (2010)
1	3.2	4.4	5.0	5.5	6.0	6.7	7.0
2	3.0	4.0	4.5	5.1	5.5	6.0	6.3
3	2.9	4.2	4.6	5.2	5.7	6.4	7.0
4	3.1	4.1	4.8	5.3	5.9	6.4	6.9
5	3.2	4.2	4.7	5.3	5.8	6.4	6.5
6	3.1	4.0	4.6	5.0	5.6	6.1	6.7

Weekly measurements of fruit size using the hand-held vernier callipers on ten fruits per treatment from 14 December 2009 to 12 February 2010 are shown on fig 4.9 for all the treatments. Fruit growth rate was similar in all the treatments from 14 to 24 December. From then the fruit growth rate in the current grower's practice and the PRD, half control treatments had higher growth rates which were not significantly different. This can be explained by that trees under PRD are not under water stress and plant water status was generally maintained. Introducing different amounts of water at different plant growth stages had no significant effects on the fruit growth rates because for all the timed PRD treatments, the fruit growth rates were not significantly different from each other.

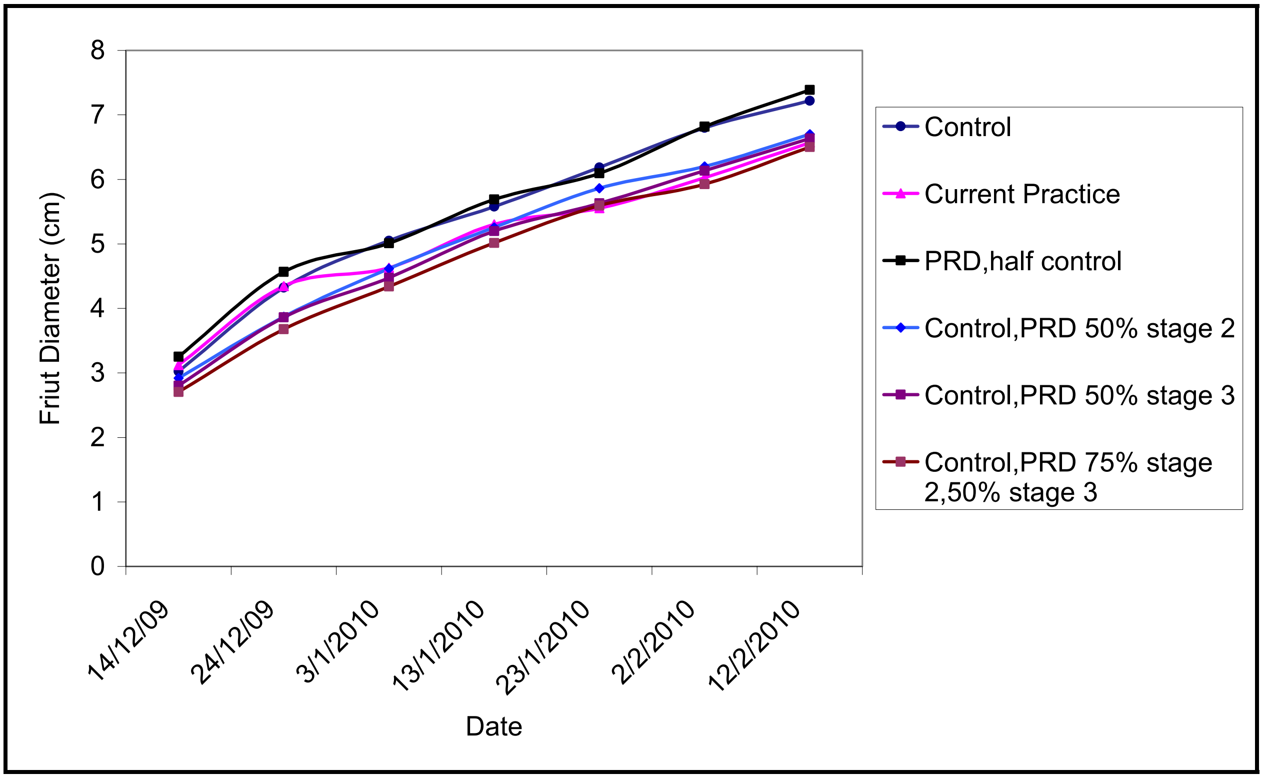

Fig 4.6 Treatments effects on weekly fruit growth rate during the 2009/2010 season.

4.8 Fruit Drop

The causes of fruit drop in these trials would not be ascertained. In the control, PRD 50% stage 3 treatment, much less fruit drop occurred. The control and current grower's practice had larger fruit drops as shown in fig 4.7. High incidences of fruit drop were not always associated or followed by a severe yield decline. High rates of fruit drop are sometimes associated with the self regulatory mechanism by the tree to control the crop load if there is an excess of fruits that it can support.

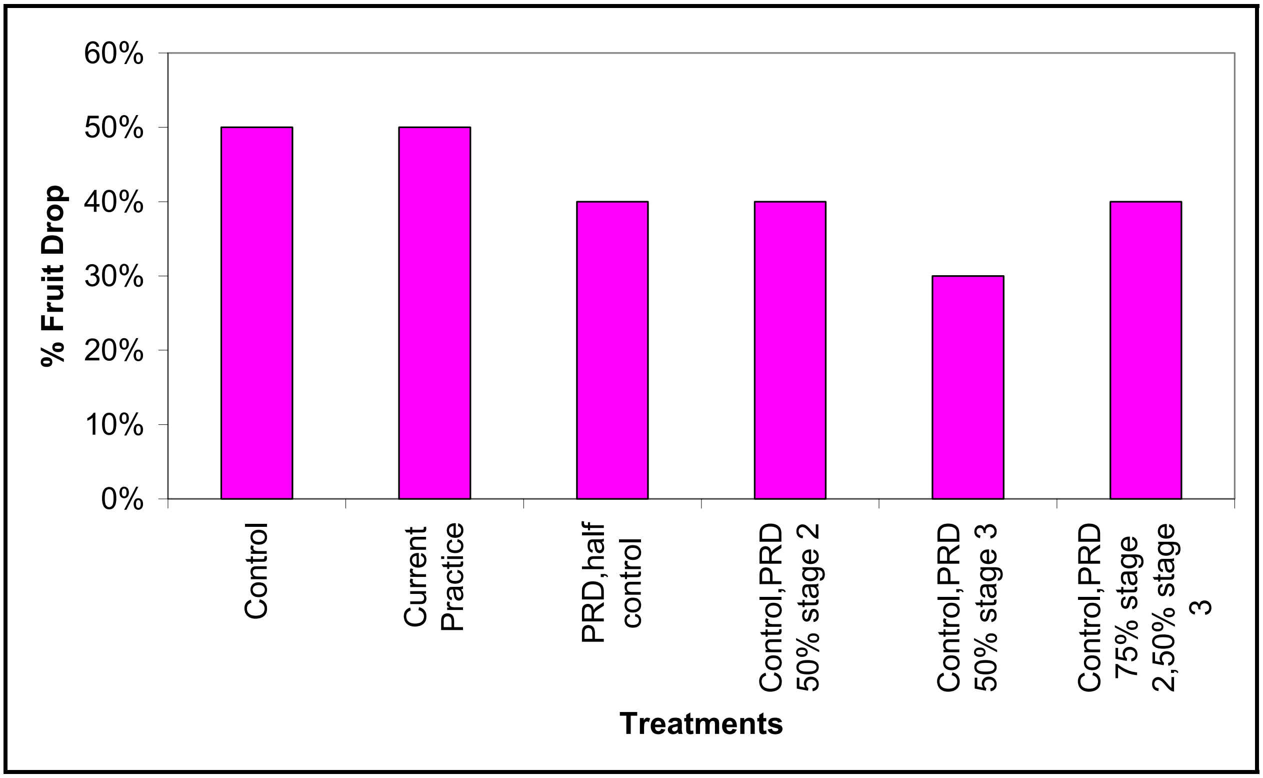

Fig 4.7 Percentage fruit drop in all the six treatments at Mazowe Citrus Estate.

4.9 Fruit yield

Maintaining crop yield and increasing water use efficiency are often cited as advantages of PRD over convectional irrigation (Kriedemann and Godwin, 2003). The results obtained in this study do not demonstrate sufficiently that there are any significant differences in yield when the PRD technique was applied at stage 2 and at stage 3 of fruit development in citrus trees. From fig 4.8, there were no significant differences in the mean yield of the timed partial root zone drying treatment and non timed partial root zone drying treatments. However there were significant difference in the number of fruits harvested when PRD was introduced at stage 2 of development. The number of fruits per tree was higher in that treatment as compared to the other treatments

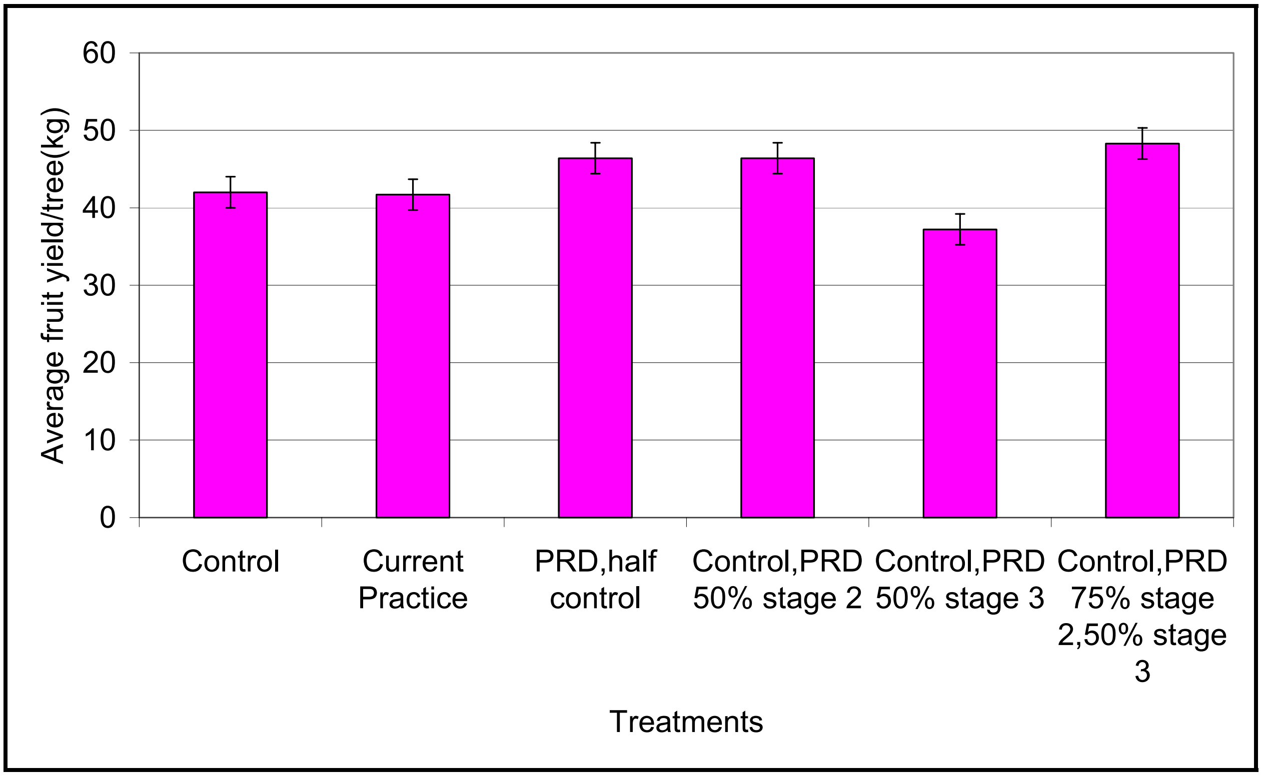

Fig 4.8 Treatments effects on average fruit yield per tree in the growing season at Mazowe Citrus Estate.

4.9.1 Crop Load

The leaf area of the trees in the six treatments which were harvested is shown in Table 4.7. Applying PRD at stage 2 of the fruit development resulted in a larger number of fruit. This response suggests that resource partitioning towards fruit set is favoured in response to timing of PRD application at stage 2 of fruit development.

Table 4.7 Crop load obtained from the trees in the different irrigation treatments during the 2009/2010 growing season.

Treatment	Fruit no. / tree	Stem diameter(cm)	Total leaf area (m)	Crop load (no. of fruit cm^{-2})
Control	184	10.3	57.5	0.31
Current Practice	152	8.2	33.3	0.22
PRD, half control	283	8.6	37.3	0.13
Control, PRD 50% stage 2	289	10.5	60.2	0.21
Control, PRD 50% stage 3	141	9.3	45.0	0.32
Control, PRD 75% stage2,50% stage3	163	10.6	61.6	0.38

.

4.10 Water Use Efficiency

Table 4.8 Water use efficiency obtained from the different irrigation treatments in the growing season per hectare.

Treatment	Treatment	Total Water received (ML/ha)	Average Yield (± 0.1 kg/tree)	Total Yield /ha (kg)	Water use Efficiency (± 0.30g/L)
Control	**1**	11.4	42	25 178	2.2
Current Practice	**2**	13.6	41.8	25 050	1.8
PRD, half control	**3**	10.2	46.4	27 815	2.7
Control, PRD 50% stage 2	**4**	11.1	46.4	27 847	2.5
Control, PRD 50% stage 3	**5**	11.3	37.2	22 320	1.9
Control, PRD 75% stage2, 50% stage3	**6**	11.3	48.3	28 976	2.6

The final water productivity, defined as the amount of harvested product per unit of water applied was analysed. Normally, when water is withheld, it causes a yield drop, and increases in water use efficiency. When water stress is considered severe, production drastically declines, decreasing water productivity to some extent. An amount of water applied at different phenological stages can increase water productivity based on the distribution throughout the irrigation periods. In table 4.10, the water use efficiency values are given. Treatment 3 gave a better result followed by treatment 4. Treatments 2 and treatment 5 gave lower results. As for treatment 2 more water was used and the total yield obtained showed that water was not used efficiently. Considering the higher volumes of water applied to the treatment, higher yields were expected. How ever in the PRD treatments, introducing PRD 75% at stage two of development and PRD 50% at stage 2 shows that the trees responded positively by using water more efficiently. Introducing the PRD treatments at stage 3 gave lower water use efficiency and significantly lower yields.

These results reflect the importance of phenological stage, emphasising the great importance of timing of PRD application, attaining high water productivity without significant yield reductions.

Increasing water use efficiency may be a means of achieving efficiency and effective water use. In agriculture, the interest is to produce more with less water, because available water for irrigated land is a limiting factor.

4.11 Fruit Quality

From the samples analysed, it was noted that differences in fruit internal quality were minimal. This is observed in table 4.11

Table 4.9 Treatments effects on fruit internal quality in the growing season at Mazowe Citrus Estate.

Treatment	Treatment	Juice % ±0.1	TSS ± 0.05	TA%± 0.01	TSS:TA
Control	1	50	9.32	0.81	11.5
Current Practice	2	48	9.16	0.77	11.9
PRD, half control	3	50	9.465	0.83	11.4
Control, PRD 50% stage 2	4	48	8.29	0.74	11.2
Control, PRD 50% stage 3	5	46	9.92	0.8	12.4
Control, PRD 75% stage2,50% stage3	6	50	9.09	0.79	11.5

Where TSS and TA are total soluble solids and total acids respectively. At citrus fruit maturation, it was observed from other findings that higher sugar content and lower acid levels at maturation are linked to increased water stress ((Peng and Rabe, 1998; Gonza´lez-Altozano and Castel, 1999). It has been proposed that additional sugar in fruit response to lower volumes of water applied to the crop is not the result of dehydration but rather extra sugar accumulated as an osmoregulatory response((Yakushiji *et* al., 1998). This response, how ever can be mitigated by timing application of PRD (Castel and Buj, 1990; Huang et al., 2000). These results are consistent with the findings in this research. Application of PRD at stage 2 of fruit development led to lower TSS levels.

The internal quality of the control slightly differed from the other five fruit samples. The TSS, which is the sugar content, was slightly lower. The TA value was also lower which lead to the TSS: TA ratio which was in the same range as the other treatments. The TSS of treatment five was slightly higher, and the TSS: TA ratio was the highest compared to the other five fruit samples. However there were no significant differences in the internal quality of five other fruit samples. There were also no significant differences in the juice percentage of the six fruit samples.

Table 4.10 Treatments effects on fruit weight in the growing season at Mazowe Citrus Estate.

Treatment	Treatment	Gross wt (kg)	Peel wt (kg)	Juice wt (kg)	Average wt (kg)
Control	1	2.89	1.45	1.44	0.24
Current Practice	2	3.65	1.38	1.27	0.22
PRD, half control	3	3.05	1.53	1.52	0.25
Control, PRD 50% stage 2	4	3.20	1.65	1.55	0.27
Control, PRD 50% stage 3	5	3.15	1.70	1.45	0.26
Control, PRD 75% stage2,50% stage3	6	3.86	1.44	1.42	0.24

The different weights of the fruits are shown in table 4.12.On gross weight of the fruit, treatment six had the highest weight, but treatment four had a higher average fruit weight. The TSS value of the current practice was relatively lower. This could have been because of the higher amount of water applied to the treatment. Higher amounts of water could have led to the lower levels of sugar. This means that water plays a role in fruit TSS development, and this is more likely linked to the photosynthetic rates since it is the process responsible for the synthesis of the sugars that make up the TSS. The higher TSS content and the lower TA caused a significant difference, in the final TSS: TA ratio between current practice and control, PRD 50% stage 3 and the rest of the other treatments. The TSS: TA value was higher. The TSS: TA ratio is very sensitive to opposing changes between TSS and TA.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Results presented in this research have shown that, after the application of PRD with half the amount of water as the control and also timing the application of PRD, we observed that timing of the application of PRD had no significant effects on the growth rate of the Navel orange fruits. These results do not show any significant differences in the yield obtained per tree across all the treatments when PRD was applied at different phonological stages of fruit growth.

However, significant differences in the number of fruits harvested per tree were observed when PRD was introduced in stage two of fruit development. This lead to an increased number of fruits harvested in the trees that were in this treatment.

Water use efficiency was significantly increased by PRD. There is also the possibility that the effects of timed PRD were not felt because of the amount of rainfall that was received during the times when stage 2 and stage 3 were introduced in the treatments. However these treatments gave favorable water use efficiency

Fruit quality was not significantly affected by the timing of PRD. The total soluble solids and the total acid of the fruits in the different treatments did not vary significantly. However, the introduction of timing of PRD at 50% at stage two led to an increase in the mean average weight of single fruit. This implies that it favors the partitioning of the assimilates to the fruit.

Fruit size was also influenced by crop load which itself was controlled by the different irrigation regimes. Application of PRD 50% at stage 2 yielded larger fruits compared to the other treatments.

5.2 RECOMMENDATIONS

For further investigations in this area of study, a drier summer would be the ideal season for this kind of an experiment. This will help in the fact that less or no rainfall will be experienced. The effectiveness of the treatments will be prominent when there is no additional water is added in the form of rainfall. These treatments should be established well before fruit set in this research such that the treatments effects can also have some impact on the fruit set stage.

Emphasis can also be placed on the effects of timing of the PRD on the transpiration rates and soil moisture measurements of the Navel trees. These measurements were not taken because of the lack of enough equipment to install in all the treatments.

From a practical point of view, to elucidate if timing PRD is really more effective than applying PRD throughout the season, we need to study some methodological aspects in the application of PRD, in order to exploit more efficiently the root to shoot signaling mechanism, such as

(1) The duration of the drying or rewatering cycling of PRD in field conditions as a function of soil type, climate, variety and root stock.

(2) The hydraulic separation between dry and wet sides parts of the root system in the PRD.

(3) The application of PRD under more efficient irrigation methods such as, subsurface drip irrigation, in order to improve water application in the root zone.

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Appendix A Significant Testing

Table A1 Fruit Yield of Citrus Trees

Fruit Yield in 6 treatments (kg/tree)							
Rep	1	2	3	4	5	6	$Y_{.j}$
1	42	41.8	46.4	46.4	37.2	48.3	262.1
2	43.8	42.6	45.3	46.6	35.6	46.8	260.7
Y_i	85.8	84.4	91.7	93	72.8	95.1	522.8
$\sum Y_{ij}^2$	3682.44	3562	4205.05	4324.52	2651.2	4523.13	22948.34

1 Calculation of the Correction Factor

$$CF = \frac{Y^2..}{tr}$$

$$= \frac{522.8}{12}$$

$$= 22776.65$$

2 Calculation of Total SS

$$TotalSS = \sum Y^2{}_{ij} - CF$$

$$= \left(42^2 + 43.8^2 + ... + 46.8^2\right) - CF$$

$= 171.69$

Calculation of Replicate SS

$$\text{Re}\,pSS = \sum \frac{Y._j{}^2}{t} - CF$$

$$= \frac{\left(262.1^2 + 260.7^2\right)}{6} - CF$$

$= 0.1667$

Calculation of Treatment SS

$$TrtSS = \sum \frac{Y^2 i}{r} - CF$$

$$= \frac{\left(85.8^2 + 84.4^2 ... + 95.1^2\right)}{2} - CF$$

=166.72

Calculation of Error SS

Error SS=Total SS-Rep SS-Trt SS

=171.69-0.1667-166.72

=5.0733

Table A2 Analysis of Variance

SOV	DF	SS	MS	F
Replication	1	0.1667	0.1667	0.164
Treatment	5	166.72	33.344	32.86
Error	5	5.0733	1.01466	
Total	11	171.69		

For the treatments, the Fcal> Ftab at 95 and 99% levels of confidence, we reject Ho: All treatment means are equal.

For the replications, Fcal<Ftab at 95 and 99% levels of confidence, we fail to reject Ho: All replicate means are equal.

Appendix B Brix temperature correction Table (from CBU, 2004)

	Brix-reading														
	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
ºC	Subtract from Brix Reading														
5	.49	.51	.52	.54	.56	.58	.60	.61	.63	.65	.67	.68	.70	.72	.73
6	.48	.49	.51	.52	.54	.55	.57	.58	.60	.62	.63	.65	.66	.68	.69
7	.46	.47	.49	.50	.51	.53	.54	.55	.57	.58	.59	.61	.62	.64	.65
8	.44	.45	.46	.48	.49	.50	.51	.53	.54	.55	.56	.57	.59	.60	.61
9	.41	.42	.44	.45	.46	.47	.48	.49	.50	.51	.52	.53	.54	.55	.56
10	.39	.40	.41	.42	.43	.44	.45	.46	.47	.48	.49	.50	.50	.51	.52
11	.36	.37	.38	.39	.40	.40	.41	.42	.43	.44	.44	.45	.46	.47	.48
12	.33	.34	.34	.35	.36	.37	.37	.38	.39	.40	.40	.41	.42	.42	.43
13	.29	.30	.31	.32	.32	.33	.33	.34	.35	.35	.36	.36	.37	.38	.38
14	.26	.27	.27	.28	.28	.29	.29	.30	.30	.31	.31	.32	.32	.33	.33
15	.22	.23	.23	.24	.24	.25	.25	.26	.26	.26	.27	.27	.28	.28	.28
16	.18	.18	.19	.19	.20	.20	.21	.21	.21	.22	.22	.22	.23	.23	.23
17	.14	.14	.15	.15	.15	.16	.16	.16	.16	.17	.17	.17	.18	.18	.18
18	.09	.10	.10	.10	.10	.11	.11	.11	.11	.11	.12	.12	.12	.12	.12
19	.05	.05	.05	.05	.05	.05	.05	.06	.06	.06	.06	.06	.06	.06	.06
20	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
	Add to brix reading														
21	.05	.05	.05	.06	.06	.06	.06	.06	.06	.06	.06	.06	.06	.06	.06
22	.10	.10	.10	.11	.11	.11	.11	.11	.12	.12	.12	.12	.12	.12	.12
23	.16	.17	.17	.17	.17	.17	.17	.18	.18	.18	.18	.18	.19	.19	.19
24	.22	.22	.23	.23	.23	.23	.24	.24	.24	.24	.25	.25	.25	.26	.26
25	.29	.29	.29	.30	.30	.30	.30	.31	.31	.31	.31	.32	.32	.32	.33
26	.35	.35	.35	.36	.36	.36	.37	.37	.37	.38	.38	.38	.39	.39	.39
27	.42	.42	.42	.43	.43	.43	.44	.44	.44	.45	.45	.45	.46	.46	.46
28	.48	.49	.49	.49	.50	.50	.51	.51	.51	.52	.52	.53	.53	.53	.54
29	.55	.56	.56	.56	.57	.57	.58	.58	.58	.59	.59	.60	.60	.60	.61
30	.62	.63	.63	.63	.64	.64	.65	.65	.65	.66	.66	.67	.67	.67	.68