EFFECT OF IRRIGATION REGIMES ON YIELD AND QUALITY OF GRAPES (*Vitis vinifera* L. cv. 'Makutupora red') IN DODOMA TANZANIA

ADAM MELKION NJOVU

A THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY OF SOKOINE UNIVERSITY OF AGRICULTURE. MOROGORO, TANZANIA.

2018

EXTENDED ABSTRACT

A growing viticulture industry in Dodoma, Tanzania has sparked a need to establish best management in irrigation practices for the improvement of quality of vine grapes and wine. Drip irrigation is important in vines cultivation in tropical semi-arid areas as it improves water productivity more than other irrigation systems. Fully irrigated grapes have shown to have higher yield and lower grape quality when compared to rain fed grapes which are coincidently under limited water availability. The use of deficit drip irrigation in Marlborough New Zealand showed substantial improvement in grape quality. However, the information of using deficit irrigation in vineyards in Dodoma is inadequate. Farmers require information on deficit levels that will give optimum grape yield and quality without detrimental effect to the vines.

A study was carried out in Dodoma Region in two seasons in 2014 and 2015 for the determination of water requirement for *Vitis vinifera* L. cv. 'Makutupora red' (crop evapontranspiration) by compensation heat pulse method. Sap flow sensors were used for measuring transpiration and soil moisture probes were used for estimating surface evaporation. The vines mean daily transpiration was 3.91 mm per day. The mean daily evaporation was 0.38mm per day. Total seasonal evapotranspiration was 581mm. Grapevine mean daily crop and basal coefficients for grapevine cv. 'Makutupora red' were0.31 (K_c) and 0.28 (K_b), respectively. The vine water consumption was high at fruit set to veraison when the canopy was fully developed.

After the determination of vine crop water requirement, the vines were subjected to deficit irrigation. Water was applied to the vines using different irrigation regimes at four irrigation levels, which were 100%, 63.5%, 56.3% and 48.9% of crop evapotranspiration

(ET_c), interacting with three irrigation methods, which were conventional drip irrigation (CDI), partial root zone drying (PRD) and root zone deficit rationing (RDR). The grape yield and quality were optimum in conventional drip deficit irrigation method (CDI) at 63.5% and 56.3% of ET_c. Moderate deficit irrigation proved to be the ideal irrigation practice for improving grape quality with a little decrease in yield.

The improvement of water productivity by application of deficit irrigation and the relationship between yield and quality components and the amount of water used by cv. 'Makutupora red' were investigated. Water productivity was higher in irrigation regimes (treatments) CDI at 63.5% and 56.3% of ET_c and in RDR at 63.5% which produced optimum yields with good grape quality. In all full irrigated regimes (at 100% of ET_c) vines gave higher grape yields and low grape quality than regimes under deficit irrigation. Pruned mass, leaf area index, berry diameter, berry weight and cluster weight (most of yield components) decreased with water deficits. Total soluble solids, alcohol, phenols and anthocyanins (most of quality components) were higher in vines under deficit irrigation than in full irrigated vines. Malic acid and tartaric acid did not show significant difference between full irrigated grapes and grapes subjected to deficit irrigation.

The finding in this study showed that the use of conventional drip irrigation method at moderate water deficits is the best option because it produced optimum grape yield and grapes of high quality. The relationship between water use, grape yield and quality showed that moderate deficit irrigation improved grape quality and minimized the use of water by vines.

DECLARATION

I, Adam Melkion Njovu, I hereby declare to the Senate of Sokoine University of Agriculture that the work that is reported in this thesis is my own original work done within the period of registration and that it has neither been submitted nor being concurrently submitted in any other institution.

_____ _____

Adam Melkion Njovu Date

(PhD Student)

The above declaration is confirmed by;

_____ _____

Prof. Henry F. Mahoo Date

(Supervisor)

_____ _____

Prof. Theodosia J. Msogoya Date

(Supervisor)

_____ _____

Prof. Bendantunguka. P. Tiisekwa Date

(Supervisor)

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ACKNOWLEDGEMENTS

I am grateful to the Almighty God for granting me access to his ceaseless revelation, wisdom and favour that saw me through my PhD in Agricultural Engineering.

A PhD is the highest level of my academic carrier, and I was able to complete this with the support of persons who were involved in the process of my research and academic undertaking. I would like to express my heartfelt gratitude to my supervisors, Prof. Henry F. Mahoo, Prof. Theodosia J. Msogoya and Prof. Bendatunguka P. Tiisekwa whose guidance, technical support, encouragement and patience enabled me to achieve my academic ambitions.

I appreciate the generous support, guidance and valuable recommendations and suggestions made by Academic staff of Department of Engineering Sciences and Technology in support of this work. I am also thankful to Sokoine University of Agriculture Technicians and supporting staff Stewart Mwanyika, Yusuph Matembo, Placid Kabalo and others for their support and suggestions. I honor the Central Zone Agricultural Research Director Mr. Leone Mrosso for giving me access to residence and research facilities at Makutupora Agricultural Research Institute. I am thankful to the Ministry of Agriculture for giving me permission and sponsorship for pursuing this course. Lastly, but not least, I want to appreciate my wife Mary Richard Njovu for her support and encouragement and my parents Mr. Melkion C. Njovu and Mrs. Winfrida M. Njovu and my brother (Eng. William M. Njovu) for their understanding, support and contributions to the success of this endeavor, may the Almighty God whom we serve bless you abundantly.

DEDICATION

This Thesis is dedicated to the Almighty God for his faithfulness and love towards me and to the service of Humanity. I also dedicate this thesis to my family and ideals, especially to my wife Mary Richard Njovu for her love, patience and help throughout my study, to my mom Winfrida Mpangala Njovu and my dad Melkion Columban Njovu for their support, sacrifice, and inspiration, to my kids Chauga Adam Njovu, Melkion Adam Njovu and Magreth Julius William for their blessings.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
APSIM	Agricultural Production Systems Simulator
ARI	Agricultural Research Institute
CDI	Conventional drip irrigation
CETAWICO	Central Tanzania Wine Company Ltd
CV	Coefficient of variation
Cv.	Cultivar
DSSAT	Decision Support System for Agrotechnology Transfer
EC	Electrical conductivity
ET_o	Reference evapotranspiration
ET_c	Crop evapotranspiration
ET_b	Crop transpiration
ET_e	Evaporation
Gm	Grand mean
FAO	Food and Agriculture Organization of the United Nations
K_c	Crop coefficient
K_b	Basal coefficient
K_e	Evaporation coefficient
LDMUA	Leaf dry mass per unit area
L.s.d	Least significant differences of means
MOA	Ministry of Agriculture
Mg	Mega gram
MWRC	Marlborough Wine Research Centre
NIIR	National Institute of Industrial Research

PRD	Partial root zone drying
RDR	Root zone deficit rationing
RDI	Regulated deficit irrigation
S.e.d	Standard error of differences means
S.e	Standard error
TMA	Tanzania Meteorology Agency
TSS	Total soluble solids
WP	Water productivity
WPQ	Water productivity by quality

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Worldwide, 69.1 million Mg of grapes are produced per year. China is leading in grape production with 11.6 million Mg per year (area under vineyards in China is 2.05 mega hectares) followed by Italy with 8.0 million Mg per year (area under vineyards in Italy is 1.69 mega hectares) (Hussein, 2010). In Tanzania grapes are grown in Dodoma Region with annual production recently reported to increase from 500 Mg in 1967 to about 19,000 Mg in 2009 (Kalimang`asi and Majula, 2014). However, the productivity is still low (2.5 Mg/ha). In Dodoma, growers harvest grapes twice per annum with one harvest during the rainy season (February- March) and another harvest during the dry season (August-September) (Mrosso, 2007).

The main hindrance to grape production in Dodoma is insufficient soil moisture during the dry season (May – November) (Hussein, 2010). It has been observed that with irrigation grape yield can be increased to between 8 and 15 Mg per ha (Mrosso, 2007). However, despite the increase in yield, there has been a decrease in grape quality (CETAWICO, 2010). The cause of low quality is probably due to over application of water at berry development stages that require less water for example from fruit set to beginning of fruit ripening (Chaves *et al.*, 2010).

A number of studies have been done to determine the optimal quality and yield of grapes through systematic regulation of amount of water supplied to the vines. Mostly deficit irrigation (DI) and partial root zone drying (PRD) have been used in regulating irrigation regimes that is the amount of water applied and the pattern of water application to the plant (Chaves *et al.*, 2010). Green *et al.* (2007) found that grape quality and yield were

optimal when using irrigation level at 30% of ET_c (crop potential evapotranspiration)on cv. ‘Sauvignon blanc’ and Ozden *et al.,* 2010 used irrigation level between 50 and 25% of ET_c and found that irrigation level below 25% lowers the yield and quality of grapes on cv. ‘Shiraz’.

In Dodoma, grape vines can be grown in most areas if water is available with the exception of areas that are water logged and with high salinity (soil electrical conductivity exceeding 2.0 mS/cm) (Mrosso, 2007). More than 90% of grapes produced in Dodoma belong to the local cultivar ‘Makutupora red’ (Kalimang’asi and Majula, 2014). The crop water requirements for cv. ‘Makutupora red’ at different growth stages of the vine must be determined for guiding grape growers to apply the correct levels of irrigation water in Dodoma. Furthermore, many models such as Aqua Crop, Decision Support System for Agrotechnology Transfer (DSSAT) and Agricultural Production System sIMulator (APSIM) are not designed for trees and vines (Chaves *et al.,* 2010). Few models are designed for vines. For example, The CropIrLog Model calculates the irrigation water requirements of the grape vines but does not estimate grape yield and quality (Green *et al.,* 2007) and uses fixed crop water requirement coefficients that may over or underestimate vine water requirement. It is therefore, necessary to determine the vines crop water requirements at different stages of berry development and to develop technical information that will associate water consumed by the vines with grape yield and quality for use in irrigation planning for grape production.

1.2 Grape Berry Development Stages

The berry and canopy development stages of grapes are complicated and differ among cultivars. In a modified Eichhorn – Lolenz system five major stages are given (Lorenz *et al.,* 1995) and 38 sub stages. The first stage involves shoot and inflorescence

development which starts at bloom to pruning to the beginning of flowering. The second stage engages flower development which begins when first flower caps loosen and ends when more than 90% of flower caps have fallen. These two foremost stages are water sensitive for roots and canopy development (Chaves *et al.,* 2010). The third stage is berry formation which starts when berry diameter is greater than 2 mm and ends when berries are nearly to start softening. This is the period when vines can be water stressed to control shoot and berry development for quality improvement (Lopez *et al.,* 2009). The fourth stage engrosses berry ripening which starts when berries begin to soften and to increase sugar content and ends at berry harvest (when berries are fully ripen) or when berries are over ripen (Lorenz *et al.,* 1995). The fourth stage requires less water (Ozden *et al.,* 2010). Senescence is the fifth stage where vine leaves start to dry and fall. This is the duration between harvest and pruning when the vines are getting a rest for the next production cycle. In tropical areas like Dodoma senescence is one to two months with partial abscission (not all leaves fall). If senescence is prolonged new leaves emerge once the soil moisture is sufficient for the vines even before pruning due to tropical hot climate (Creasy and Creasy, 2009).

To reduce the complication, Keller and Tarara (2010) identified three berry development phases which starts at bloom and ends at harvest.

1.2.1 Stage I: Berry formation to lag phase

The first phase is related to berry formation. This phase starts at bloom and goes on until the berries have reached half of their size for about 45- 60 days. During this time, the berry is formed and rapid cell division occurs. The berry expands in volume and accumulates solutes such as tartaric and malic acids, but little sugar. Tartaric acid has the highest accumulation in the skin. It accumulates during the initial stages of berry

development and provides acidity for winemaking, thus making it a critical component. Malic acid has the highest content in the flesh and is also important in the final wine making process. Tannins, phenols and anthocyanin accumulate during the first growth phase of the berry and are present in the skin and seeds. Tannins are responsible for bitterness and astringency, making it important especially for red wine quality characteristics including color, stability and mouth feel.

1.2.2 Stage II: Lag phase to veraison

The lag phase is distinguished by a pause in berry growth, during which seed embryos start to grow rapidly. At the start of the lag phase, berries have reached at least half of their final size. Following the 5 to 10 days lag, cells expand and continue to accumulate acids and tannins, which reach their maximum levels at veraison. During this phase, seeds reach their final size by 10 to 15 days before veraison.

1.2.3 Stage III: Veraison to berry ripening

The third phase starts with veraison and includes the softening and coloring of the berry, accumulation of soluble solids (sugars), and reduction in acids. During this phase, the berry doubles in size and several changes occur. The malic acid content is reduced, although this is strongly correlated with climate. Warm region grapes typically have less malic acid, whereas cooler regions produce grapes with higher levels of malic acid. Seed tannins also decline during the second growth phase as a result of oxidation where they become fixed to the seed coat. Some of the significant changes occurring after veraison are an increase in compounds like glucose and fructose from sucrose.

1.3 Climate, Crop Water Requirement and Irrigation Regimes

1.3.1 Climate

Rainfall, temperature, wind, atmospheric pressure, solar radiation and air humidity are important climatic factors in vineyard cultivation. Climate data are required for calculating reference evapotranspiration (ET_o) as a basic step in estimating the crop water requirement. The reference evapotranspiration is determined by Penman-Monteith Equation (Green *et al.*, 2007). On average, a grapevine needs around 195 mm of water for sustenance during the growing season (Green, 2005).

Warm periods are crucial during flowering, fruit set and ripening stages. Temperatures between 17 ˚C and 30 ˚C are ideal for vine cultivation with low relative humidity between 60 and 70% (Chaves *et al.,* 2010; Jones *et al.,* 2010). In the past, grapes were not grown in tropical areas and on starting to cultivate the quality of grapes and wine produced were poor due to earlier failures to control high temperatures and humidity. Recently due to microclimate and good timing of the vintage there are some areas which are now producing high quality wine and table grapes like Brazil, China, Chile and Dodoma in Tanzania where humidity is low and temperature is low in the night (Jones *et al.,* 2012; Anderson *et al.,* 2012; Mahoo *et al.,* 1999).

1.3.2 Crop water requirement

The crop water requirement is the quantity of water required by a crop in a given period of time for its growth and development under field conditions (Chaves *et al.,* 2010). The crop water requirement includes water consumed by the plant and water lost through evaporation and therefore is referred to as the crop evapotranspiration. Green *et al*. (2007) determined the vine evapotranspiration by using sap flow meters with an assumption that the soil evaporation is negligibly small for an efficient drip irrigation system. However,

Dodoma being semi-arid water lost by evaporation must be included in the determination of vine evapotranspiration (Mahoo *et al.*,1999; Teixeira *et al.*, 2007; Mahinda, 2014).

1.3.3 Irrigation regimes

An irrigation regime is a water distribution pattern to an intended plant which is molded by a combination of an irrigation scheduling, method, and level (Chaves *et al.*, 2010). It is necessary to identify the optimum irrigation regime that will improve quality without affecting yield and quality of the fruits (Chaves *et al.*, 2010). This can be achieved by systematically regulating the amount of irrigation water. The effect of irrigation levels on grapes depends mainly on the vines tolerance to water stress. Green *et al*. (2007) got good results of grape quality and yields by using irrigation levels between 50 and 30% of ET_c on cv. 'Sauvignon blanc'**.** Conventional deficit irrigation (CDI), partial root zone drying (PRD) and root zone deficit rationing (RDR) methods will be used in this study to mold water distribution patterns in the vines' root system.

i. Conventional deficit irrigation method (CDI)

Conventional deficit irrigation method is commonly used, where the amount of water applied to the plant is reduced below the crop requirement (ETc) (Ozden *et al.*, 2010). It has the advantage of water saving and improving fruit quality and water is uniformly applied on the vine root zone. CDI is simple to apply and install without the complications of water regimes manipulation. It only requires timing of berry development stages and water rationing (Chaves *et al.*, 2010).

ii. Partial root zone drying method (PRD)

In Partial Root Zone drying method, water is periodically supplied in alternation, to only one side of the root system whereas the other one is allowed to dry. By withholding water

from half of the root system (Fig.1.1), the soil dries out slowly whilst the other part is kept frequently irrigated. After a certain period of time, 'wet' and 'dry' zones are alternated and the former 'wet' side starts to dry out (Stoll, 2000). The sides to be irrigated are changed in a ten to fourteen days rhythm so that one part of the root system does not remain permanently wetted or dried (Chaves *et al.*, 2010). It has the advantage of saving water and improving fruit quality. PRD is limited to soil types and irrigation systems where the root system of vines can be subjected to discrete (localized) wet and dry zones. It has a high risk of damaging the roots in the drying zone if not properly managed and monitored (Lopez *et al.*, 2009). Previous studies indicate that there is still a need to investigate the effect of PRD and CDI on grapevine physiology and grape quality (Balint, 2011). Sadra (2009) and Green (2005) found that PRD improves grape quality but similar gains were also achieved with conventional deficit irrigation.

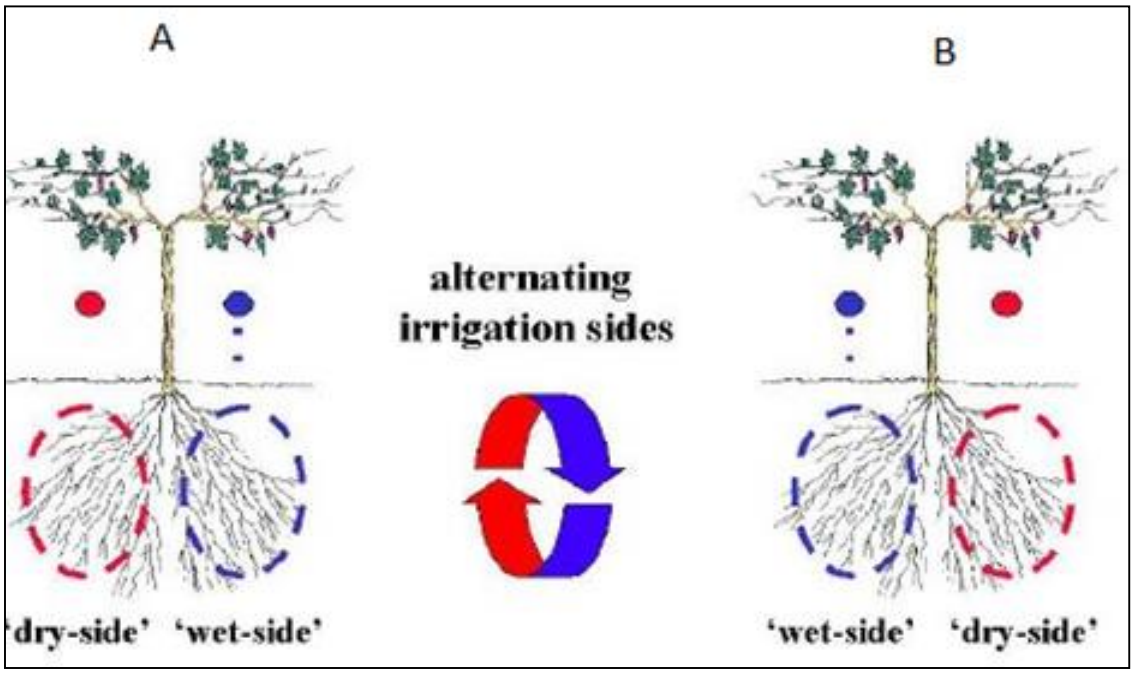

Figure 1.1: Implementation of partial root zone drying

iii. Root zone deficit rationing method

The operation and setting of root zone deficit rationing is similar to (PRD) but the danger of over stressing one side of the root zone is eliminated by rationing the amount of water applied to the vines such that one side gets one third of water applied to the vine. The sides are changed alternatively after every fourteen days period.

1.4 Grape Yield and Quality

The grape yield is the amount of fruits per unit area (CETAWICO, 2010). For 5 to 35 years old vines, grape yields remain the same if the vines are subjected to similar management and field conditions (Mrosso, 2007). Average yield per hectare in Dodoma is 2.5 Mg in rained vineyards and 8 to 15 Mg in irrigated fields. In other grape growing countries, yield per hectare has been reported to be 5.4 Mg in Spain, 16 Mg in China and 17.5 Mg in USA (CETAWICO, 2010). In Dodoma quality of ripe grapes (at maturity) is assessed to be of good quality when the grape total soluble solids - TSS (measurement of the concentration of sugars per unit of water in the grape berry) is at least 22˚Brix, pH at 3.3 to 3.6 and titratable acids ranging between 4 g/l and 7 g/l (Mrosso, 2007).

1.4.1 Phenols and anthocyanins

Wine consumers are also interested in phenols and anthocyanins compounds which are responsible for wine taste, mouth feel and color. It has also been reported that these compounds have health advantages and act as antioxidants (Tiisekwa, 1998 and Chaves *et al.,* 2010). Total phenol compounds have been found to range between 200 mg/l and 425 mg/l and total anthocyanins from 50 mg/l to 200 mg/l from 14 cultivars of grapes studied in USA by Yang *et al.* (2009).

Roby and Matthews (2004) found that the berry growth and ripening in grapes are affected by the amount of water consumed by the vine which also affects the composition of phenols and anthocyanins in grapes. They further found that grapes from water stressed vines at 60% of ET_c had a 45% increase in phenols and anthocyanins compounds over grapes from full irrigated vines. Post veraison (after fruit maturity) water application cuts had ignorable effect on yield (El-Ansary *et al*., 2005).

1.4.2 Total soluble solids stability

Stability and biosynthesis of total soluble solids including sugar content, phenols and anthocyanins in grapes are favoured by warm day time temperature (17°C-30°C) and cool nights (10°C – 20°C) (Mori, 2005). This is in agreement with Coombe (1987), who reported that with 30 °C day temperatures and low night temperatures at 10 °C resulted in a higher sugar content in berries than warm nights, which may be associated with a higher translocation rate of sugar into berries. Dodoma has an average maximum daytime temperature of 26-29 °C and the minimum temperature ranges between 11 and 18°C and cool night temperature ranges between 8 and 15°C (TMA, 2013) which is perfect temperature for getting with grapes high sugar content.

1.5 Statement of the Research Problem

Studies done on vine water requirement and the effect of deficit irrigation on grape yield and quality have shown to differ among vine cultivars (Chalves *et al*., 2010). Different vine cultivars have different water requirements. Therefore, determining the crop water requirement for each cultivar is necessary (Lopez *et al*., 2009). If crop coefficient for a given vine cultivar is available, water crop requirement can then be computed using reference evapotranspiration. In a situation where the crop coefficient is not available, the

water requirement has to be measured. The use of lysimeters for measuring crop water requirement is mostly used but it is expensive, difficult to install on the field and is restricted to few plants (Green *et al.*, 2007). In Dodoma, it was seen that irrigated vines produce lower quality of grapes than non-irrigated vines but yield per area was higher in irrigated vines than in non-irrigated vines (CETAWICO, 2010). This underscore the need to determine the crop water requirement of cv. 'Makutupora red' and the amount of water that can be applied to the vines that will give optimum yield and quality of cv. 'Makutupora red'. There is no information on either water requirement or crop coefficient of cv. 'Makutupora red' and no study has been carried out to determine the water requirement of grapes grown in Dodoma and their response to deficit irrigation. This study was carried out to find crop water requirement of cv. 'Makutupora red' using an indirect method called Compensation Heat Pulse Method and the response of grape vines to deficit irrigation.

1.6 Objectives

1.6.1 Overall objective

The overall objective of this study is to establish irrigation regimes for improved yield and quality of grapes (*Vitis vinifera* L. cv. 'Makutupora red') in Dodoma Region.

1.6.2 Specific objectives

The specific objectives of the study include the following;

i. To determine crop water requirement of grape vine cv. 'Makutupora red' from pruning to grape maturity.
ii. To determine yield and quality of grapes cv. 'Makutopora red' under different irrigation regimes.

iii. To establish relationship between water consumption, yield and quality of grapes for irrigation planning.

1.7 Significance of the Study

Dodoma Region is a semi-arid area and grape production gives an opportunity for small holders to improve their livelihood (Kalimang`asi and Majula, 2014). Moreover, the demand of grapes in Dodoma has increased due to an increase in both processing capacity from 200 Mg in 2005 to 4000 Mg of grapes in 2010 (CETAWICO, 2010) and a reliable market within East and Central Africa. About 100 Mg of grapes and 500 000 liters of wine are exported to Kenya, Uganda, Rwanda, Zaire and Burundi (CETAWICO, 2010; Hussein, 2010). Furthermore, the potential of grape production from irrigated vineyards in Dodoma requires a thorough investigation of the effect of irrigation regimes to the vines that will optimize the quantity and quality of grapes. Also, investigation of the response of cv. 'Makutupora red' to water stress is prioritized over other cultivars because it has acclimatized to Dodoma environment and contributes to more than 90% of grapes grown in Dodoma.

1.8 Outline of the Thesis

An overview over the effects of deficit irrigation on grapevines and review of studies of irrigation methods that have been used to optimize grape yield and quality and the status of grape production in Dodoma, Tanzania are given in the introductory Chapter 1. Chapter 2 explains the indirect determination of crop evapotranspiration of *Vitis vinifera* L. cv. 'Makutupora red' by compensation heat pulse method and soil moisture probes at different stages of berry development. In Chapter 3 the effect of irrigation regimes on grape yield and quality is investigated, the results are given for selection of suitable irrigation regimes for optimization of grape yield and quality. Chapter 4 covers the

relationship between grape yield, quality and grapevine water consumption. General discussion and conclusions are given in Chapter 5.

1.9 References

Balint, G. (2011). Impact of different irrigation strategies on grapes and wine quality of four grapevine cultivars (*Vitis* sp.) in cool climate conditions. An investigation into the relationships among ABA, water status, grape cultivar and wine quality. Thesis for Award of PhD Degree at Brock University, St. Catherines Ontanario, Canada, 429pp.

CETAWICO (2010). *Annual Company Progress Report.* Cantina di Sociale, Hombolo Township, Dodoma, Tanzania. 10pp.

Coombe, B. (1987). Influence of temperature on composition and quality of grapes. *Acta Horticulture* 206: 23 – 35.

Chaves, M. M., Zarrouk, O., Francisco, R., Costa, J. M., Santos, T., Regalado, A. P., Rodrigues, M. L. and Lopes C. M. (2010). Grapevine under deficit irrigation: hints from physiological and molecular data. *Annals of Botany* 105: 661 – 676 .

Creasy, C. and Creasy, L. (2009). Grapes. *Crop Production Science* 16(281): 105 – 156.

El-Ansary, D., Nakayama, S., Hirano, K. and Okamoto, G. (2005). Response of Muscat of Alexandria table grapes to pot-veraison regulated deficit irrigation in Japan. *American Journal of Enology Viticulture* 44(1): 5 – 9.

Green, S., Clothier, B. and Deurer, M. (2007). Measuring and modeling stress response of grapevines to soil-water deficits. In:*Understanding and Modeling Water Stress Effects on Plant Growth Processes.*(Edited by Davidson, P.), The Horticulture and

Food Research Institute of New Zealand Ltd., Marlborough District Council, New Zealand. pp. 357 – 385.

Green, S. G. (2005). *Marlborough Crop Water productivity Report.* Marlborough District Council, NewZealand. 39pp.

Hussein, S. (2010). Value chain analysis of grapes in Tanzania. Dissertation for Award of MSc Degree at Sokoine University of Agriculture, Morogoro.124pp.

Jones, G. D. (2010). Spatial analysis of climate in winegrape growing regions in the Western United States. *American Journal of Enology and Viticulture* 61(3): 313 – 326.

Jones, G. R. (2012). *Climate, Grapes, and Wine: Structure and Suitability in a Variable and Changing Climate The Geography of Wine: Regions, Terrior, and Techniques*. Springer Press, USA. 255pp.

Kalimang`asi, N. and Majula, R. A. (2014). The economic analysis of the smallholders grape production and marketing in Dodoma Municipal: A case study of Hombolo. *International Journal of Scientific and Research* 4: 2250 – 3153.

Keller, M. and Tarara, J. (2010). Warm spring temperatures induce persistent season-long changes in shoot development in grapevines. *Annalsof Botany* 106: 131– 141.

Lopez,I., Ramirez, P. and Morales, J. (2009). Influence of a deficit irrigation regime on the quality of wine made from white grapes grown in semi arid areas. *Journal of Food Quality* 32(4): 481 – 490.

Lorenz, D., Eichhorn, K., Bleiholder, H., Klose, R. and Weber, E. (1995). Phenological growth stages of the grapevine, *Vitis vinifera* L. ssp. vinifera. Codes and descriptions according to the extended BBCH scale. *Australian Journal of Grape Wine Research* 1: 100–103.

Mahinda, A. (2014). Effect of drip irrigation on the production and economic returns of soghurm in semi arid areas of Tanzania. Dissertation for Award of MSc Degree at University of Nairobi,Nairobi, Kenya, 94pp.

Mahoo, H., Young, M.and Mzirai, B. (1999). Rainfall variability and its implications for the transferability of experimental results in the semi arid areas of Tanzania. *Tanzania Journal of Agricultural Science* 2: 127 – 140.

Mori, S. (2005). Decreased anthocyanin biosynthesis in grape berries grown under elevated night temperature condition. *American Journal of Horticultural Science* 105: 319 – 330.

Mrosso, L. (2007). Development of vineyard cultivation in Dodoma. *Proceedings of Central Zone Agricultural Research Steering Committee Meeting*. Dodoma, Tanzania, 23 May, 2007. 14pp.

Ozden, M., Vardin, H., Simsek, M. and Karaaslan, M. (2010). Effects of rootstocks and irrigation levels on grape quality of *Vitis vinifera* L. cv. 'Shiraz'. *African Journal of Biotechnology* 9(25): 3801 – 3807.

Roby, G. and Matthews, M. (2004). Relative proportions of seed, skin and flesh, in ripe berries from Cabernet Sauvignon grapevines grown in a vineyard either well irrigated or under water deficit. *Australian Journal of Grape Wine Research* 10: 74 – 82.

Sadra, V. (2009). Does partial root-zone drying improve irrigation water productivity in the field? A meta-analysis. *Irrigation Science* 27: 183 – 190.

Stoll, M. (2000). Effect of partial root zone drying on grapevine physiology and fruity quality. Thesis for Award of PhD Degree at University of Aldelade, New Zealand, 231pp.

Teixeira, A., Bastiaanssen, W. and Bassoi, L. (2007). Crop water parameters of irrigated wine and table grapes to support water productivity analysis in the Sao Francisco river basin. *Agricultural Water Management* 94: 31 – 42.

Tiisekwa, B. (1989). Improvement of traditional manufacturing of sorghum beer (Mtama) in Tanzania. Dissertation for Award of PhD Degree at Rijks University , Belgium, 227pp.

TMA (2013). Weather forecast. from Tanzania meteorological agency certified in aeronautical meteorological services.[http://www.meteo.go.tz/index.php] site visited on 10/11/2013.

Yang, J., Martinson, E. and Liu, H. (2009). Phytochemestry profile and antioxidant activities of wine grapes. *Journal of Food Chemistry* 116: 332 – 339.

CHAPTER TWO

2.0 DETERMINATION OF WATER CONSUMPTION OF GRAPES (*Vitis vinifera* L. cv. 'Makutupora red') IN DODOMA, TANZANIA BY COMPENSATION HEAT PULSE METHOD

Abstract

It has been observed that fully irrigated grapes grown in Dodoma, Tanzania have lower quality than rain fed grapes. Grapevine water consumption determination was a prerequisite for irrigation planning as information about grapevine water requirement was not adequate for cv. 'Makutupora red' in Dodoma. Water used (Transpiration) by mature grapes (*Vitis vinifera* L. cv. 'Makutupora Red') vines grown for wine production without stress during two growing seasons (2014 - 2015) was measured using compensation heat pulse method. Vines were irrigated using drip irrigation system and sap flow sensors with CR 1000 data logger were used to determine daily water consumed by vines cv. 'Makutupora red' at different stages of berry development. Furthermore, water lost through evaporation was also determined on daily basis by using soil moisture probes (Mercker, 2011). Data were collected in 2014 from May to mid-September and in 2015 from April to Mid-August in Dodoma Region in Tanzania at Makutupora Agricultural Research Centre. Average daily transpiration was 3.95 mm per day in 2014 and 3.88 mm per day in 2015. The average daily evaporation per plant was 0.37 mm per day in 2014 and 0.40 mm per day in 2015. Total seasonal evapotranspiration was 584 mm in 2014 and 578 mm in 2015 (Grapevine season length for cv. 'Makutupora red' is 175 days which is about 5.5 Months). Grapevine mean daily crop and basal coefficients for *Vitis Vinifera* cv. 'Makutupora red' were 0.31 (K_c) and 0.28 (K_b) respectively. The difference between

crop and basal coefficient was small as a result of reduced water losses through evaporation due to small exposed and wetted soil surface in drip irrigation system. For other irrigation methods, the crop coefficient will be higher than in drip system due the increase of evaporation coefficient (K_e). The vine water consumption was high at fruit set to veraison when the canopy was fully developed.

Key words: Evaporation, Transpiration, Compensation heat pulse method, Crop coefficients

2.1 Introduction

The determination of grape vines water requirements is very important in drip irrigation planning (Prichard, 2001). There is also a need to establish reliable values of water quantities that can be beneficially used by plants at determined levels with assurance of production and good quality of grapes and wine without causing detrimental effects to the vines (Teixeira *et al.,* 2007). Research on the use of compensation heat pulse method to determine vines transpiration has been done on some vine cultivars (Chaves *et al*., 2007; Green *et al.,* 2003). Green *et al.* (2003) found that water required by vines differs among cultivars and this underscores the need to test other cultivars. Soil evaporation has to be determined together with transpiration under drip irrigation because some of the water applied to the plants is lost through soil evaporation and can be high in tropical arid and semi-arid areas due to wind and low air humidity (Medrano *et al.*, 2015). Penman Monteith Equation is being used for estimating crop water requirement by considering transpiration which consists of the vaporization of liquid water contained in plant tissues and evaporation which is the process whereby liquid water is converted to water vapor (vaporization) and removed from the evaporating surface (Allen *et al.,* 1998). Evaporation and transpiration are two processes occurring simultaneously and is difficult

to separate them. The two processes are estimated together as the crop water use called evapotranspiration. Lysimeters have been used in measuring evapotranspiration (Zhang *et al.,* 2011). There have been efforts to determine evaporation and transpiration separately either directly or by using models. The use of soil moisture probes has the advantage of continuously measuring and recording soil moisture contents at different soil depths such that water lost through evaporation on the soil surface can be determined (Mercker, 2011; Ginger and Keefer, 2008). Therefore, evapotranspiration is obtained by combining the determined plant transpiration by compensation heat pulse method and evaporation by soil moisture probes to a depth of 0.15. For deep rooted crops (i.e., where the depth of the maximum rooting zone is > 0.6 m), the amount of transpiration from the evaporating soil layer (to a depth of 0.15 m) is small and water lost in that upper layer can be assumed to occur due to evaporation only.

In Dodoma, grape vines can be grown in most areas if water is available with the exception of areas that are water logged and with high soil salinity (soil electrical conductivity exceeding 2.0 mS/cm) (Mrosso, 2007). Two cultivars have been registered as suitable in Dodoma which are 'Chenin blanc' and 'Makutupora red'. More than 90% of grapes produced in Dodoma belong to the local cultivar 'Makutupora red' (CETAWICO, 2010; Mrosso, 2007; Lwelamira *et al.,* 2015; Hussein, 2010). Previous studies put more emphasis on increasing production of grapes by irrigation and improving the grape market but little have been done on investigating the crop water requirements for cv. 'Makutupora red' at different growth stages of the vine for getting information that will guide grape growers to apply the correct levels of irrigation water in Dodoma. Furthermore, many models such as Aqua Crop, Decision Support System for Agrotechnology Transfer (DSSAT) and Agricultural Production System sIMulator (APSIM) are not designed for trees and vines (Chaves *et al.,* 2010). It is therefore,

necessary to determine the transpiration and evaporation components of cv. ‘Makutupora red’ which will be basic information for Dodoma grape growers in planning their irrigation methods and schedules. The grapevine is a perennial plant which under good management its lifespan can exceed 50 years (Mrosso, 2007). In each vintage (production cycle), vines leaves are pruned and the new emerging leaves come with bunches bearing berries and the cycle ends after harvesting the fruits and letting the vines to rest for about 15 to 30 days before starting a new production by pruning again (Hussein, 2010).

The objective of this study was to determine crop water requirement of grape vine cv. ‘Makutupora red’ from pruning to grape fruit maturity by;

i. To determining grapevine transpiration at different berry development stages by heat pulse compensating method and evaporation by soil moisture probes.
ii. To establish crop coefficients of cv. ‘Makutupora red’ at different berry development stages.

2.2 Materials and Methods

2.2.1 Description of the study area

The study was carried out in Dodoma at Makutupora Agricultural Research Institute (ARI-Makutupora) which is located at latitude $5^{0}58'669''$ S and longitude $35^{0}46'093''$ Eabout 26 km North of Dodoma Municipality (Hussein, 2010) (Fig. 2.1). The area lies at an altitude of 1050m above sea level (Mahinda, 2014). The annual rainfall at ARI Makutupora ranges from 530 mm to 660 mm with rains falling between December and March. April to November is a dry season (Mahoo *et al.*, 1999; Msongaleli, 2015). The average annual daily air humidity is 65%, minimum temperature is 15 °C and maximum temperature is 32 °C (TMA, 2013).

2.2.2 Description of the plant material

The plant material was *Vitis vinifera* L. cv. 'Makutupora red' planted in 2002 on 0.4 ha at ARI-Makutupora with spacing of 1.5m within rows and 2.5 m between rows. The vineyard plant population was 2667 vines/ha (10000/3.75). The rows are in East-West orientation (for maximizing the capture of sunlight energy for photosynthesis) with the sun overhead at noon (Mrosso, 2007). During the trial the vines were thoroughly managed with timely weed control, pruning, pest control, de-suckering, manure addition and vermin control such that the vines did not succumb to any stress. The vines were trained to bilateral cordons trellis (extension of trunk horizontally to Eastern and Western side) at 1 m above the ground and in each season were pruned to three bud spurs. Farmyard manure was added in the soil at 20 Mg/ha in February (2014) and chemical inputs ridomil 6 g/*l*, anvil 0.5 m*l*/*l* and sumithion 1 m*l*/*l* were timely sprayed for the control of powdery mildew, dawn mildew and pests, respectively (Medrano *et al*., 2015).

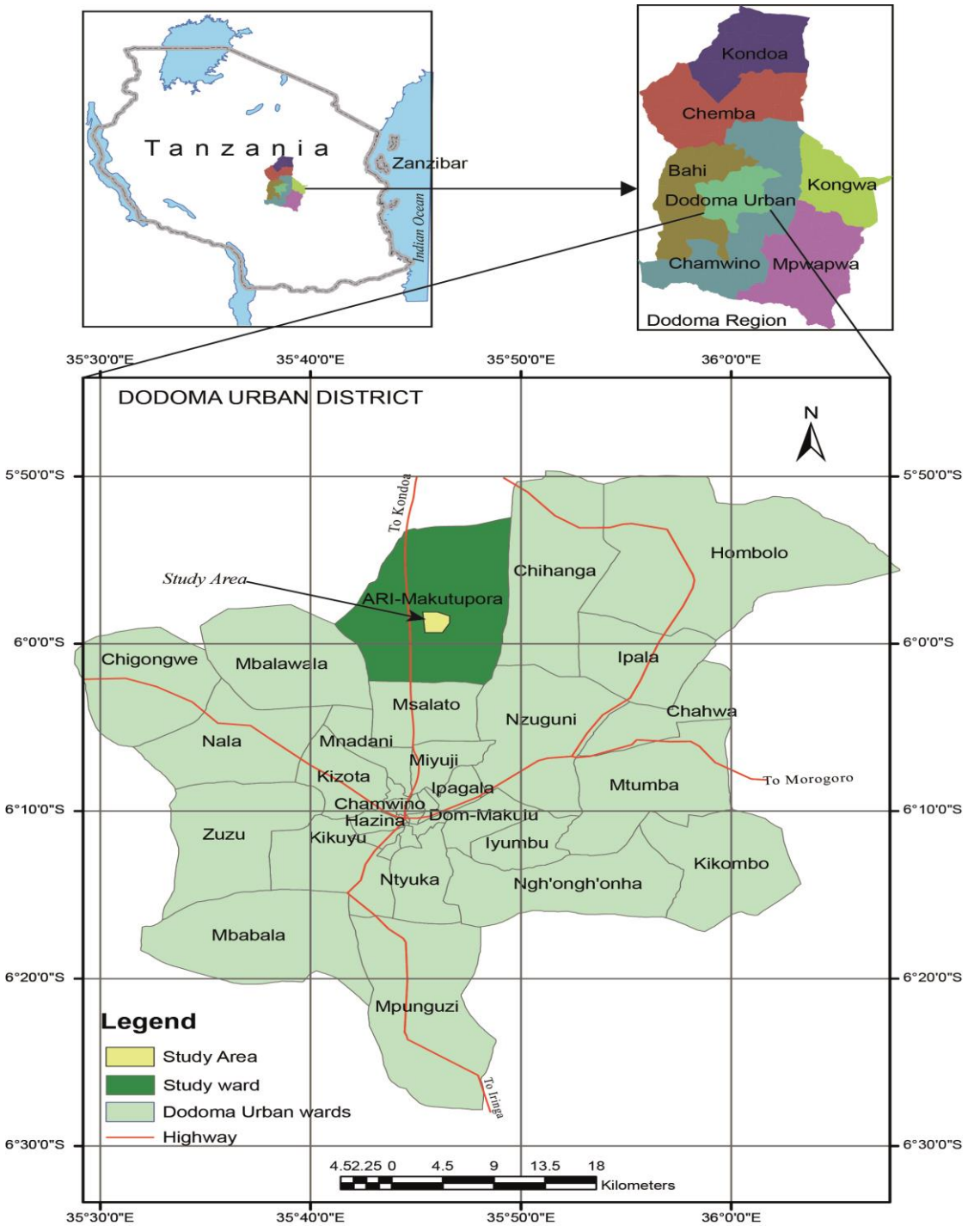

Figure 2.1: Location of the study area at Makutupora. Source: Rwebugisa (2008).

2.2.3 Soil

The dominant soils at ARI-Makutupora vine yard is sand clay to sand clay loam. The soils are well drained and ideal for vine cultivation (Stoll, 2000). The root zone of cv. 'Makutupora red' was taken to be 100 cm because for irrigated vines about 60 percent of vine roots grow in the top 60 cm of soil. The remaining 40 percent of roots grow mostly within 60 -100 cm soil profile horizon (Rees and Doyle, 2010).

2.2.4 Soil sampling

The vine yard was installed in November 2013 with drip irrigation and six vines were selected from two adjacent rows. Previously, the vines were irrigated by furrow surface irrigation. Soil samples were collected in iron cores and composite soil samples were collected by auger from the experimental field at 5 levels of the root zone horizons at 20 cm depth interval from 4 randomly selected points on the field of study (vine yard under drip irrigation = 0.4 ha) and were sent to the Sokoine University of Agriculture Soil Science laboratory for analysis.

i. Soil physical analysis

In the laboratory samples were prepared for the determination of soil textural class by method explained by Cassel and Klute (1986), soil bulk density by the core method (Cassel and Klute, 1986) and soil moisture characteristics at different suction pressures as explained by Cassel and Klute (1986). The suction levels used at field capacity and wilting point were 30 and 1500 kPa respectively (Brady, 1986).

ii. Soil chemical analysis

Soil pH and Electrical conductivity were also determined with a digital pH/Cond meter (WTW product, Tetracon 325) for assessing the suitability of the soil for vines.

2.2.5 Water quality analysis

Samples of borehole water that was used for irrigation were collected on 15th day of every month in 2014 and 2015 for determination of water electrical conductivity and pH by using a digital pH/Cond meter (WTW product, Tetracon 325). This was necessary for investigating the suitability of borehole water that was used for irrigating the vines during the study.

2.2.6 Measurement of crop transpiration

Drip irrigation was used for distributing water to the vines with one drip line in each row and one emitter at each vine. Water was applied daily with emitters' discharge rate at 2.0 liters/h. The amount and time of daily water application were obtained by FAO Penman-Monteith estimations of reference evapotranspiration and recommended crop coefficients values for vines with adjustments for ground cover from which the amount of water to be applied per tree was computed on daily basis as explained by Allen *et al.* (1998). The vines transpiration (ET_b) which is the water consumed by the plant under no water stress was determined by indirect method (Compensation heat pulse method) as explained by Green (2009) on daily basis. Vine parameters were measured from six plants including stem diameter, bark thickness, and the volume fractions of timber and wood which were determined experimentally from wood samples taken from the monitored vines.

The sap flow measuring set comprised of:

- A solar pannel of 80 watts for recharging the battery
- A 12 volts battery for supplying thermal energy to the heater probes
- Heater control switches for controlling current to the heater probes.
- Electric wire cabbles for connections of data logger to the probes and other accessories.
- 6 upstream temperature probes (sensors)

- 6 Heater probes
- 6 downstream temperature probes (sensors)
- CR 1000 data logger for timed recording of signals from the sensors and sending heat pulse signals to the control swich such that heat pulses are conveyed to the heater probes after every thirty minutes and for storing data that can be communicated to the computer through com 1 port.
- Tool set for drilling holes on the selected trees

The arrangement and installation are shown in Fig. 2.2 and Fig. 2.3.

Figure 2.2: Sap flow measuring set, the data logger, a battery and heater switches are caged for safety and shading from weather

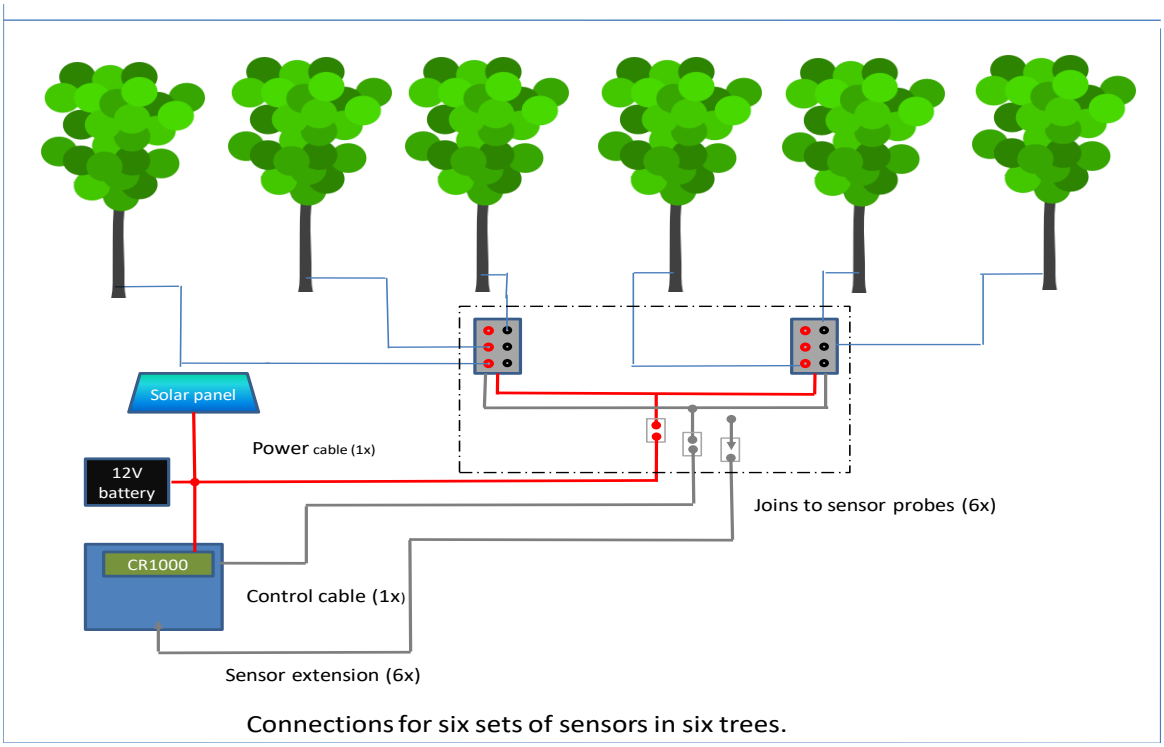

Figure 2.3: Sap flow measuring set installation diagram

Six sap flow measuring units were installed (6 X 2 channels made in New Zealand by TanzFlo NZ Ltd) on one stem of each tree of six randomly selected vines. Each unit had two temperature probes placed asymmetrically (at 5 mm below and 20 mm above the heater probe) either side of a line heater that was inserted radially into the tree stem. The holes were in parallel and drilled into the stem at heights of about 0.3-0.5 m above the ground (Suvocarev *et al.*, 2013). To avoid shaking and enlarging the drilled holes a metal guide was used. The probes were covered by aluminium foil sheets to reduce the effect of external weather to the probes as shown in Appendix 1. The heater introduced a brief 1-2 s pulse of heat into the stem, and a data logger measured the time delay (t_z) for an equal temperature rise at both sensors for each tree. The time delay was used to calculate heat-pulse velocities, and a theoretical factor was used to calculate volumetric rates of sap flows (Green, 2009).

The vines were drip irrigated on daily basis from pruning to berry maturity for 135 days. Each temperature probe had two thermocouples. In each tree a heater probe and two sensors (temperature) probes were installed (Fig. 2.4).

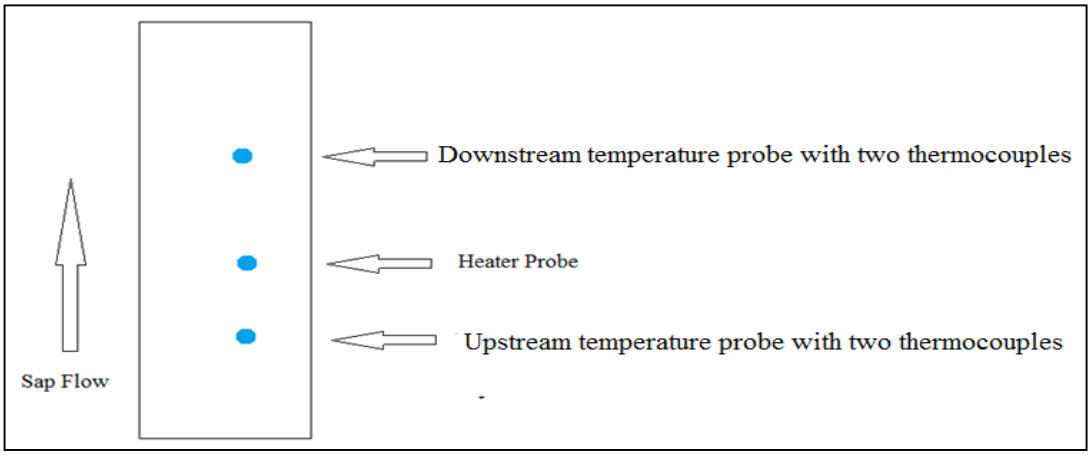

Figure 2.4: Heater probe and temperature probes

As explained before the data logger was set to record time at which the temperatures of both probes (upstream and downstream probes) were the same and a series of half-hour values of t_z were recorded by the data logger for all six trees. Also, the logger gave a signal to the heater control switches to release heat pulses once in every 30 minutes interval.

$$V = \frac{(X_d + X_u)}{2t_z} \quad \text{.... (1)}$$

Where: V = Raw heat pulse velocity

X_d = Downstream distance from the heater probe = 15 mm

X_u= Upstream distance from the heater probe = 5 mm

t_z (s) = Time delay for the temperatures at points X_d and X_u to become equal.

Equation (1) implies that following the application of an instantaneous heat-pulse, the centre of the heat-pulse is convected downstream, from the heater, to reach the point mid-way between the two temperature sensors after a time t_z. Equation (1) is particularly well suited to data logging since it only requires electronics to detect a null temperature difference and an accurate timer to measure t_z. The t_z was the only data that needed to be recorded, since the distances X_u and X_d remained constant (Green, 2009).

The CR 1000 data logger detected and recorded values of t_z which were transferred to the PC for further analysis. After computing values of *V*on daily basis, they were then adjusted to get the corrected heat pulse velocity V_c using Equation (2) by procedure described by Green (2009).

$$\boldsymbol{V_c = a + bV + cV^2} \quad \text{(2)}$$

where: a, b and c are correction factors to take into account the effect of the installation wound width; The wound width was 2.8 cm selected from Table 2.1 depending on the size of the drill bit as explained by Green (2009);

Table 2.1: Wound corrections for Equation (2)

Wound width (mm)	*a*	*b*	*c*
0	0	1	0
1.6	0.39	1.36	0.04
2.0	0.81	1.2	0.06
2.4	1.18	1.07	0.09
2.8	1.52	0.96	0.12
3.2	1.83	0.88	0.17
3.6	2.09	0.82	0.22

Source: Green (2009).

The corrected heat-pulse velocity, V_c, was determined, and then converted to the actual sap flow. Marshall (1958) showed that if the sap and woody matrix are considered to

form a homogeneous medium, then the sap flux density, *J* [m s-1], can be calculated (Equation 3).

$$\boldsymbol{J = P(0.33 + M)V_c} \quad \text{……(3)}$$

Where, *P* = Wood density in kg/m^3 (oven dry weight of wood/green volume) and

M = Moisture content (wet weight - oven dry weight)/oven dry weight) of sapwood.

The density and moisture content of the sapwood are both physical properties of the woody matrix. The factor 0.33 in Equation (3) is the specific heat of dry wood, which is assumed to be constant. In the analysis, an alternative expression for *J* was used (Equation 4), which was developed by Suvocarev *et al*. (2013) by considering the sapwood to comprise 3 phases of gas, solid and liquid with appropriate physical and thermal properties. The working equation is given by:

$$\boldsymbol{J = (0.505F_m + F_L)V_c} \quad \text{……. (4)}$$

Where, F_m and F_l are the volume fractions of wood and water, respectively. The factor 0.505 in Equation (4) is related to the thermal properties of the woody matrix and is assumed to be constant within and between species (Green, 2009). F_m and F_l were determined experimentally from wood samples taken from the six vines in each season. The fresh weight of each wood sample was determined just right after extracting from the tree trunk. The dimensions (base radius and height) of the sample were measured to determine the wood sample volume (V_t). Later, the sample was oven-dried to determine the mass of dry wood (M_m) and the mass of water (M_l) contained in the fresh sample. Then F_m and F_L were computed as:

$$\boldsymbol{F_m = \frac{M_m}{\rho_m * V_t}} \quad \text{……(5)}$$

$$\boldsymbol{F_l = \frac{M_l}{\rho_l * V_t}} \quad \text{……(6)}$$

where: ρ_m is dry wood density taken as 1530 kg m^{-3} (Green, 2009) and ρ_l is water density taken as 1000 kg m^3. F_m and F_l values were found to be 0.52 and 0.38 in the first season (2014) and 0.51 and 0.39 in the second season (2015) respectively. Fresh wood samples were extracted from six trees in each season (Table 2.2). Then, the half-hour volume sap flux, F_t (*l/h*) was determined by integrating the *J* values at the two depths following the procedure described by Green (2009) for which the cambium radius of each vine trunk was measured and used in computation using a software developed by Green (2009). Daily transpiration values (*l/day*) were obtained by summing up the half-hour values.

Table 2.2: Fractions of wood and water

	2014		2015	
Tree	F_m	F_l	F_m	F_l
1	0.52	0.38	0.53	0.38
2	0.54	0.35	0.50	0.41
3	0.52	0.38	0.49	0.41
4	0.53	0.38	0.51	0.37
5	0.50	0.40	0.52	0.40
6	0.51	0.37	0.50	0.38
Fraction means	**0.52**	**0.38**	**0.51**	**0.39**

Daily transpirations in mm/day was obtained by dividing daily transpiration in L/day by wetted area in m^2(P_w) measured at 30 cm soil depth of each of the six plants under the experiment by method explained by Green *et al.* (2007) (Table 2.3).

Table 2.3: Average percent of wetted area at 30 cm soil depth (Pw)

	Wetted Diameter (cm)	**Wetted area (m^2)**	**Wetted area (%)**
1	0.90	0.64	0.17
2	1.10	0.95	0.25
3	1.40	1.54	0.41
4	1.20	1.13	0.30
5	1.30	1.33	0.35
6	1.30	1.33	0.35
Average	**1.20**	**1.15**	**0.31**

2.2.7 Measurement of soil evaporation

Four moisture probes were installed in the soil at the bases of four vines in the vineyard very close to the vines stems, about 30 cm from the stem. The soil moisture content was determined by the conventional method described by Gardner (1986). Samples were taken from four stations close to the probes from each of the five horizons 0-20 cm, 20-40cm, 40-60cm, 60-80 cm and 80-100cm and kept in air-tight iron cores until they were weighed and thereafter were oven-dried at 105°C for 48 hrs and weighed again. The gravimetric soil water content S_g which was the difference between the wet and dry mass expressed as a percentage of the dry mass was converted into volumetric moisture content by the following Equation (7);

$$S_m = \frac{\rho_{g*}S_g}{\rho_w} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(7)}$$

Where S_m = Volumetric moisture content

S_g= Gravimetric moisture content

ρ_g = Soil bulk density = M_d/V_c in g/cm^3

ρ_w= Density of water in g/cm^3

M_d = Soil oven dry mass of the core in g

V_c = Core volume in cm^3

Volumetric moisture content values obtained were used to calibrate the moisture probes by comparing with probe readings taken at corresponding depths at the same time of soil sampling. The soil samples for calibration were collected during the rainy season when moisture in the soil within a given layer is almost uniformly distributed. The regression equation for the calibration of moisture probes is expressed by Equation (8) (Table 2.4 and Fig. 2.5).

Table 2.4: Calibration of moisture probes

Probe Reading*	Soil Moisture (%)	Soil Moisture Fitted Values (%)
34.60	16.01	16.05
38.42	16.89	16.76
38.61	16.81	16.79
39.14	16.87	16.89
40.27	17.11	17.10
41.59	17.33	17.34
46.54	17.96	18.26
48.01	18.73	18.53
48.88	18.29	18.69
51.64	19.61	19.21
54.50	19.82	19.74
55.04	19.93	19.84
55.33	19.94	19.89

*Probe reading calibrated to soil moisture content (correlation = 0.97; S.e = 0.208)

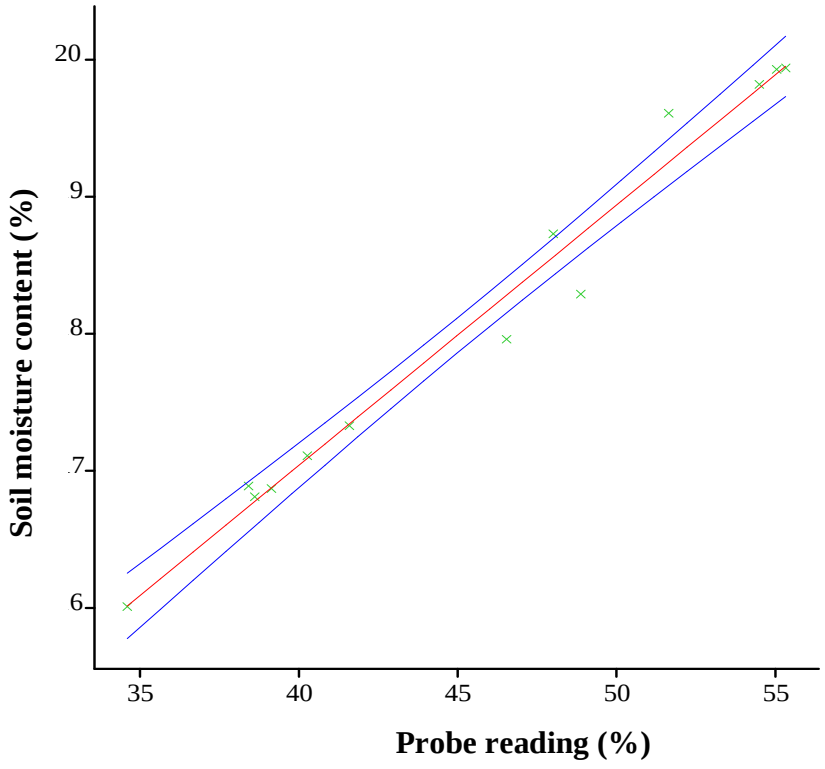

Figure 2.5: Fitted and observed soil moisture content relative to probe readings with 95% confidence limits.

$$S_{mc} = 0.1852 * P_{mc} + 9.64 \text{ ... ...(8)}$$

Correlation coefficient r^2= 0.977 and standard error of observations S.e = 0.208

Where,

S_{mc} = Volumetric soil moisture content derived from calibration of probe reading

P_{mc} = Moisture probe reading

The moisture probes were reinstalled on four vines under drip irrigation. The probes were shielded by wire mesh to avoid vermin interference (Appendix 1). Then daily soil evaporation was estimated by measuring daily moisture depletions from the top soil wetted surface to a depth of 15 cm on daily basis as explained by Allen *et al*. (1998); Farah (2001); Mercker (2011); Zerizghy and Rensburg (2013). Drip irrigation was applied daily and daily soil evaporation was estimated by using the soil moisture balance Equation 9;

$$(SM_i - SM_f) * 0.1852 * Z_e * A_w * 1000 * \left(1 - \frac{2}{3} * f_c\right) = I + P - RO = E + T + D \text{ ... ...(9)}$$

Where;

SM_i = Initial probe reading at the end of an irrigation event on the soil surface layer

SM_f = Final probe reading just before another irrigation event on the soil surface layer

0.1852 = Conversion factor from probe readings difference to actual soil moisture content depleted

I = Amount of water added to the soil surface layer due to irrigation in liters

P = Amount of water added to the soil surface layer due to precipitation in liters

RO = Amount of water reduced from the soil surface layer due to precipitation runoff in liters

E = Evaporation in liters

T = Transpiration from the soil surface layer in liters

DP= Deep percolation loss from the topsoil layer if soil water content exceeds field capacity in liters

Z_e = Evaporating depth = 0.15 m

A_w = Wetted and exposed area on the surface =0.09 m^2 (diameter of wetted area = 0.34 m)

f_c= Effective fraction of soil surface covered by vine canopy (0.15 – 0.50)

In the case of drip irrigation, where the majority of soil wetted by irrigation is beneath the canopy and shaded, a consideration of the soil surface and wetting patterns is required to accurately estimate total evaporation from the soil. In this case, the value for wetted area A_w was reduced to account for the effects of shading of emitters by the plant canopy on the evaporation rate from wetted soil by using a general approach recommended by Allen *et al.* (1998) which was to multiply A_w by (1-(2/3)*f_c). Transpiration on the surface soil layer was taken to be negligibly small ($T \approx 0$). The amount of transpiration from the evaporating soil layer is small and can be ignored, except for shallow rooted crops with depth of the maximum rooting zone less than 0.6 m (Allen *et al.*, 1998).

2.3 Data Analysis

The data of water consumed by six plants were recorded by CR 1000 data logger and were downloaded to a computer and then daily water consumptions were computed for the two seasons, using Tanzflow software (Green, 2009). Surface evaporation data were recorded on daily basis from the soil moisture probes by data logger and down loaded to a computer. The average daily means of transpiration and evaporation on every berry development stage were computed and compared by subjecting data to the analysis of variance (ANOVA) using GENSTAT 13 (Stern *et al.*, 2004). Duncan multiple range test at a probability of 5% was applied to assess significant differences on transpiration and evaporation at different stages of vintage (pruning to berry maturity).

2.4 Results and Discussions

2.4.1 Soil Physical Properties

The clay, sand and silt particles distribution were found to be 34.01, 50.38 and 15.61 % respectively. The soil is classified as sand clay loam (Table 2.5).

Table 2.5: Soil particle distribution across soil depth

Soil depth (cm)	Clay* (%)	Sand* (%)	Silt* (%)
Level 0-20 cm	31.59a	**58.72c**	9.69a
Level 20-40 cm	**37.20b**	53.09b	9.71a
Level 40-60 cm	35.31ba	44.73a	17.26b
Level 60-80 cm	35.55ba	47.19a	**20.96b**
Level 80-100cm	33.12ba	46.45a	20.17b
Gm	**34.01**	**50.38**	**15.61**
S.e.d	2.52	1.56	3.22
L.s.d	5.38	3.33	6.86

*Means of 8 samples of soil
Means followed by the same letter in a column were not significantly different, based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05). S.e.d = standard errors of differences of means, L.s.d = Least significant differences of means and Gm = grand mean

Sand particles percentage was higher in the upper layer but decreased with depth. Clay and silt particles percentages were higher in the deep layers. Fine particles on the soil surface (clay and silt) are carried away by water (run off) and wind, this can contribute to low percentage of fine particles on the soil surface. Msongaleli (2015) found on the soil upper surface the sand particles percent was as high as 79 at Hombolo in Dodoma. Mahinda (2014) found the sand particles on the upper layer (15 cm) were 70% at Makutupora in Dodoma. These observations show that on the soil surface sand particles are dominant.

2.4.2 Soil hydrological properties

Soil moisture content at saturation, field capacity and wilting point were found to be 32.86, 19.15 and 12.83 % respectively (Table 2.6).

Table 2.6: Soil moisture characteristics across soil depth

	Soil moisture %		
Soil depth cm	**Saturation point***	**Field capacity***	**Wilting point***
Level 0-20 cm	41.65a	**21.76a**	**11.14a**
Level 20-40 cm	41.73a	27.53c	14.56b
Level 40-60 cm	41.76a	23.04ab	13.06ab
Level 60-80 cm	42.29a	**26.63bc**	**12.29ab**
Level 80-100cm	43.08a	**27.15c**	**13.06ab**
Gm	**42.10**	**25.22**	**12.85**
S.e.d	1.74	1.9	1.43
L.s.d	3.55	3.87	2.91

*Means of 8 samples of soil
Means followed by the same letter in a column were not significantly different, based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05). S.e.d = Standard errors of differences of means, L.s.d = Least significant differences of means and Gm = Grand mean

The water holding capacity (soil moisture content at field capacity – soil moisture content at wilting point) in the upper layer (level 0-20 cm) was relatively higher than the next level (20 – 40 cm) although sand percentage is higher in the upper layer. This is due presence of organic matter on the upper layer. In the deeper soil layers (60-80 cm and 80-100 cm), water holding capacity was higher due to the increase of silt percentage and a decrease I sand percentage.

2.4.3 Soil chemical properties

The soil pH ranged between 4.78 and 6.58 and the soil average electrical conductivity (EC) was 401.76µS/cm (Table 2.7). The soil pH at the higher horizon was higher than in the lower layers. Mahinda (2014) at ARI Makutupora and Msongaleli (2015) at Hombolo village in Dodoma observed that soil pH at the top horizon 0-15 cm depth was higher

than in deep horizons (pH range to a depth of 120 cm was between 6.0 and 7.5 at ARI Makutupora and between 4.5 and 6.0 at Hombolo village). This is common in semi-arid areas where leaching is low (Ahmed, 2012). The reason for difference in pH is limited leaching due to low rains and capillary movement of water in soil that leaves salts on the upper layer after evaporation. There wasn't a significant difference in soil electrical conductivities across soil depth. The Soil electrical conductivity was found to be 0.40 mS/cm (Table 2.7) and suitable for vines cultivation (NIIR, 2004).

Table 2.7: Soil electrical conductivity and pH

Soil depth (cm)	**Soil EC* (µS/cm)**	**Soil pH ***
0-20	294.50a	**6.58b**
20-40	430.00a	5.54ab
40-	441.00a	4.86a
60-80	435.00a	4.78a
80-100	372.50a	**4.91a**
Gm	**394.60**	**5.33**
S.e.d	70.23	0.29
L.s.d.	153.02	0.63

*Means of 8 samples of soil
Means followed by the same letter in a column were not significantly different, based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05). S.e.d = Standard errors of differences of means, L.s.d = Least significant differences of means and Gm = Grand mean.

2.4.4 Water quality

The borehole water pH ranged between 6.5 and 7.5 and electrical conductivity between 0.57 mS/cm and 1.10 mS/cm (Table 2.8). The borehole water was classified as good for irrigation (Chaves *et al*., 2010). The borehole electric conductivity and pH values were found to be higher in September, October and November (very dry period), when air temperature is high and humidity low and there is no dilution of ground water by rainfall.

Table 2.8: Variations of borehole water electrical conductivity and pH in a year

Month	EC* (mS/cm)	pH*
January	**0.565a**	**6.60a**
February	0.570a	6.70ba
March	0.675ab	6.70ba
April	0.705cb	6.80cba
May	0.810dc	6.90dcba
June	0.855ed	7.00dcba
July	0.908ed	7.20dcb
August	0.950fe	7.30dc
September	1.050gf	7.30dc
October	**1.100g**	**7.40d**
November	1.054gf	7.40d
December	0.706cb	6.80cba
Gm	**0.829**	**7.0**
S.e.d	0.059	0.27
L.s.d	0.130	0.60

*Means of EC and pH for 4 samples of water
Means followed by the same letter in a column were not significantly different, based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05). S.e.d = Standard error differences of means, L.s.d = Least significant differences of means and Gm = Grand mean

2.4.5 Transpiration and evaporation

The sap flows measured in six vine trees were recorded after every 30 minutes for 135 days in each experiment then were summed up to obtain daily water use and then means of daily water use in fifteen days interval were computed and compared between intervals to determine water use by vines at different stages of fruit development Daily mean transpiration per plant was 3.95 mm/day in 2014 and 3.88 mm/day in 2015 (Table 2.9).

Table 2.9: Variation of daily vine transpiration across berry development stages

Berry development stage	Time (days)	ET_b* (2014) (mm/d)	ET_b* (2015) (mm/d)	ET_b* (Av) (mm/d)
Wool	0 - 15	1.43a	2.16a	**1.79a**
Bud burst	15 - 30	2.86b	3.03cb	2.95b
Flowering	30 - 45	1.95a	2.57ba	**2.26a**
Fruit set	45 - 60	5.66fe	4.92gf	**5.29f**
Berry enlargement	60 - 75	4.36dc	4.25fe	4.30dc
Beginning of berry touch	75 - 90	6.05f	3.74dc	4.90fed
Berry touch	90 - 105	4.67d	4.63fe	4.65fed
Beginning of veraison	105 - 120	4.95ed	5.52g	5.23fe
Veraison	120 - 135	3.63cb	4.10ed	**3.86c**
Gm		**3.95**	**3.88**	**3.91**
S.e.d		0.41	0.37	0.30
L.s.d		0.81	0.73	0.59

*Means of 15 readings of grapevine daily transpiration per vine (ET_b).
Means followed by the same letter in a column were not significantly different, based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05). S.e.d = Standard error of differences of means, L.s.d = Least significant differences of means and Gm = Grand mean.

The fractions of daily transpiration per plant of daily reference evapotranspiration per plant (basal crop coefficient) were 0.28 in 2014 and 0.27 in 2015 as shown in Table 2.10. These coefficients are the ratio of transpiration to the reference evapotranspiration (ET_b/ET_o). Transpiration was law at initial stage (wool stage), It then increased to maximum at mid stage (from fruit set to beginning of veraison, where transpiration was rather constant) and then decrease at final stage (veraison). The final stage is the berry ripening stage where the vines consume less water.

Daily transpiration (ET_b) per vine was found to be between 27 and 28% of the daily reference evapotranspiration per plant in both seasons. Similar results were reported by Green *et al.* (2003) in Marlborough District in New Zealand who found that basal crop coefficients for cultivars *Vitis vinifera* L, 'Cabernet sauvignon' and 'Chardonnay' were 0.3. The basal coefficients of cv. 'Crimson' and 'Autumn royal' which were seedless

grapes were found to be 0.67 and 0.82 respectively about 12.9 mm per day (Suvocarev*et al.*, 2013) values which do not show any drought tolerance. Er-Raki *et al.* (2013) found that crop coefficients were 0.22 at initial stage, 0.45 middle stage, and 0.30 at final stage (average 0.33) on *Vitis vinifera* L. cv. 'Perlette' and cv. 'Superior' which were similar to our results. This indicates that the vine crop water requirement differs among cultivars and that the cv. 'Makutupora red' is draught tolerant.

Table 2.10: Variation of daily vine transpiration coefficient across berry development stages

Berry development stage	Time (days)	K_b* (2014)	K_b* (2015)	K_b* (Av)
Wool	0 - 15	0.11a	0.13a	**0.12a**
Bud burst	15 - 30	0.20b	0.21cb	0.21b
Flowering	30 - 45	0.13a	0.18ba	0.15a
Fruit set	45 - 60	0.42d	0.40e	**0.41d**
Berry enlargement	60 - 75	0.32c	0.31d	0.31c
Beginning of berry touch	75 - 90	0.43d	0.27d	0.35c
Berry touch	90 - 105	0.33c	0.31d	0.32c
Beginning of veraison	105 - 120	0.32c	0.37d	0.34c
Veraison	120 - 135	0.24b	0.26dc	**0.25b**
Gm		**0.28**	**0.27**	**0.28**
S.e.d		0.03	0.03	0.21
L.s.d		0.06	0.05	0.04

*Means of 15 readings of grapevine daily basal crop coefficient (K_b).
Means followed by the same letter in a column were not significantly different, based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05). S.e.d = Standard error of differences of means, L.s.d = Least significant differences of means and Gm = Grand mean

Daily average evaporation per plant was 0.37 mm/day in 2014 and 0.40mm/day in 2015 (Table 2.11) and the mean daily evaporation coefficient was 0.027 (Table 2.12). Soil evaporation in drip irrigation was low for example in 2014 was 8.5% and in 2015 was 9.3% of the amount of water applied to the vines (ET_c).The low evaporation was due to small wetted and unshaded area.

Table 2.11: Variation of daily evaporation across berry development stages

Berry development stage	Time in days	ET_e* (mm/d) (2014)	ET_e* (mm/d) (2015)	ET_e* (mm/d) (Av)
Wool	0 - 15	0.42b	0.47b	**0.44cb**
Bud burst	15 - 30	0.25a	0.40ba	0.32a
Flowering	30 - 45	0.21a	0.40ba	0.30a
Fruit set	45 - 60	0.33ba	0.39ba	0.37ba
Berry enlargement	60 - 75	0.27a	0.49b	0.37ba
Beginning of berry touch	75 - 90	0.34ba	0.41ba	0.37ba
Berry touch	90 - 105	0.42b	0.30ba	0.36ba
Beginning of veraison	105 - 120	0.63c	0.38ba	**0.50c**
Veraison	120 - 135	0.45b	0.34a	**0.40cb**
Gm		**0.37**	**0.40**	**0.38**
S.e.d		0.03	0.03	0.18
L.s.d		0.05	0.04	0.03

*Means of 15 readings of grapevine daily evaporation under drip irrigation (ET_e).
Means followed by the same letter in a column were not significantly different, based on Duncan multiple range test at a probability value of ≤ 5% ($P \leq 0.05$). S.e.d = Standard error of differences of means, L.s.d = Least significant differences of means and Gm = Grand mean.

It was found that the rate of evaporation was high at wool stage (0.44 mm/day), just after pruning and thereafter it decreased at flowering stage (to 0.3 mm/day) and then increased in the later stages (to 0.37 mm/day). At wool stage, the leaves were emerging and could not cover the ground from sun rays. As a result, more water evaporated from the exposed soil. Greer *et al.* (2010) found that evaporation was high at early stage of berry development due to absence of sufficient canopy cover of the vines. Just after pruning a decrease in evaporation at flowering stage was a result of reduction of exposed soil surface caused by a well-developed leaf canopy (Williams, 2012). At later stages (fruit set to veraison) the rate of evaporation increased to 0.5 mm/day due to a decrease of air humidity and an increase of air temperature during the daytime.

Table 2.12: Variation of daily evaporation coefficient across berry development stages

Berry development stage	Time (days)	K_e*(2014)	K_e* (2015)	K_e* (Av)
Wool	0 - 15	0.032cd	0.029cb	0.031cb
Bud burst	15 - 30	0.017a	0.028cba	0.023a
Flowering	30 - 45	0.015a	0.027cba	0.021a
Fruit set	45 - 60	0.024cba	0.032cb	0.028cba
Berry enlargement	60 - 75	0.02ba	0.035c	0.028cba
Beginning of berry touch	75 - 90	0.024cba	0.03cb	0.027cba
Berry touch	90 - 105	0.03cb	0.02a	0.025ba
Beginning of veraison	105 - 120	0.041d	0.025ba	0.033c
Veraison	120 - 135	0.03cb	0.021a	0.026cba
Gm		**0.026**	**0.027**	**0.027**
S.e.d		0.03	0.027	0.21
L.s.d		0.059	0.053	0.042

*Means of 15 readings of grapevine daily evaporation coefficient under drip irrigation (K_e).
Means followed by the same letter in a column were not significantly different, based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05). S.e.d = Standard error of differences of means, L.s.d = Least significant differences of means, and Gm = Grand mean

It was observed that losses due to evaporation were minimized to 9% of water applied to the vines because with drip irrigation water losses by runoff, deep percolation and seepage are eliminated and the wet surface which is exposed to evaporation is reduced to a small fraction (Mahinda, 2014).

The water used by the vines slowly increased for the first 30 days from pruning. Then decreased a bit at 30-45 days and then increased to maximum (5.65 mm/day) when the vines had developed full canopy at 60-75 days. From 75 to 120 days the daily water consumption of the vines was fairly constant. At 120 to 135 days from pruning the vines water consumption was decreasing. At early stage just after pruning the vines consumed less water but with an increase relative to the canopy development (Suvocarev *et al*., 2013). In the first 30 days there was minimum leaf cover on the wetted area so evaporation was substantially contributing to the evapotranspiration. 45 days after pruning, the leaves effect was reducing the exposed wetted area but still the vines used more water because at that time the canopy was developing vigorously while the vines

needed more water to suffice vine photosynthesis (Fig. 2.6). After 120 days the vines used less water because berries had reached ripening stage (Elgendy *et al*., 2012). Theoretically there is an increasing water use at initial stage then at middle stage constant water use and finally decreasing water use at final stage (Kose, 2014).

Table 2.13: Variation of daily vine evapotranspiration across berry development stages

Berry development stage	**Time in days**	**ET_c*(mm/d) (2014)**	**ET_c*(mm/d) (2015)**	**ET_c* (mm/d) (Av)**
Wool	0 - 15	1.84a	2.63a	**2.23a**
Bud burst	15 - 30	3.11b	3.43cb	3.27b
Flowering	30 - 45	2.16a	2.97ba	2.57a
Fruit set	45 - 60	5.99f	5.31fe	5.65e
Berry enlargement	60 - 75	4.63dc	4.74ed	4.69dc
Beginning of berry touch	75 - 90	6.38f	4.16dc	**5.27ed**
Berry touch	90 - 105	5.09ed	4.92ef	5.01d
Beginning of veraison	105 - 120	5.57fe	5.90f	5.74e
Veraison	120 - 135	4.09c	4.43d	**4.26e**
Gm		4.31	4.28	4.30
S.e.d		0.03	0.03	0.18
L.s.d		0.05	0.04	0.03

* Means of 15 readings of grapevine daily evapotranspiration under drip irrigation (ET_c).
Means followed by the same letter in a column were not significantly different, based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05). S.e.d = Standard error of differences of means, L.s.d = Least significant differences of means and Gm = Grand mean

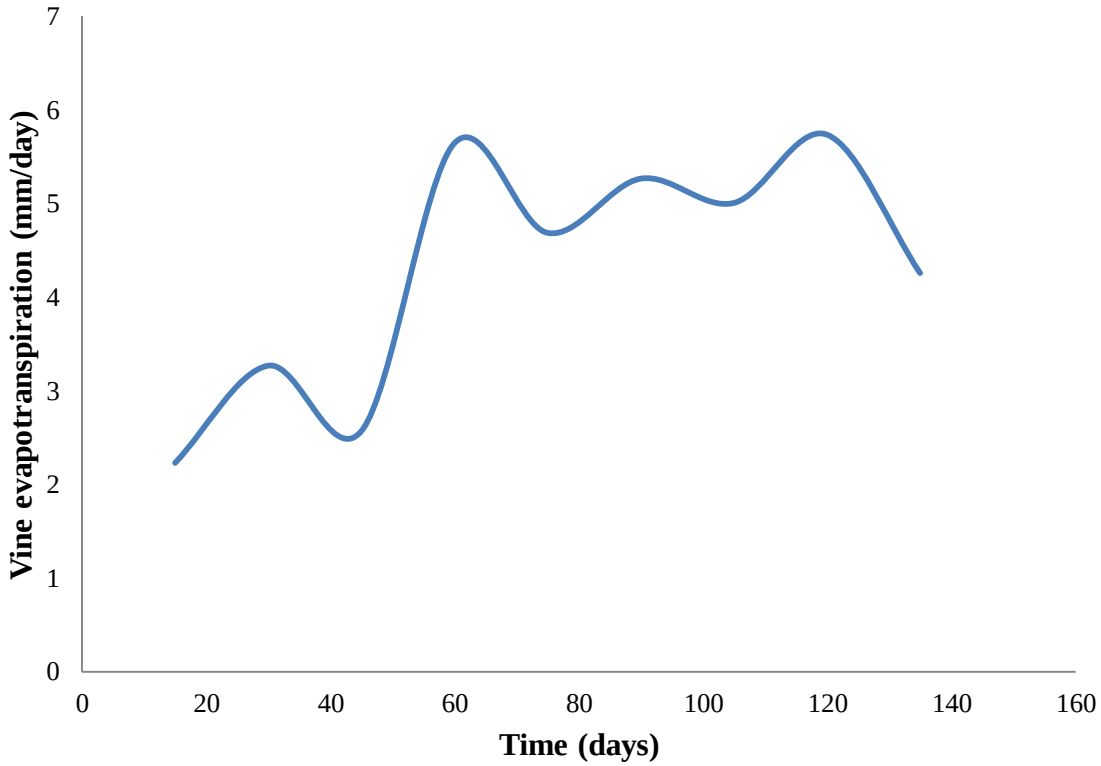

Figure 2.6: Variation of daily vine evapontranspiration in a season

Table 2.14: Variation of crop coefficient across berry development stages

Berry development stage	Time in days	K_c (2014)*	K_c (2015)*	K_c (Av)*
Wool	0 - 15	0.14a	0.16a	**0.15a**
Bud burst	15 - 30	0.22b	0.24cb	0.23b
Flowering	30 - 45	0.15a	0.20ba	0.18a
Fruit set	45 - 60	0.44d	0.43g	**0.44e**
Berry enlargement	60 - 75	0.34c	0.34fe	0.34d
Beginning of berry touch	75 - 90	0.46d	0.30ed	0.38d
Berry touch	90 - 105	0.36c	0.33ed	0.35d
Beginning of veraison	105 - 120	0.36c	0.40gf	0.38d
Veraison	120 - 135	0.27b	0.28dc	**0.27e**
Gm		**0.304**	**0.298**	**0.301**
S.e.d		0.03	0.027	0.21
L.s.d		0.059	0.053	0.042

* Means of 15 readings of grapevine daily crop coefficient (K_c).
Means followed by the same letter in a column were not significantly different, based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05). S.e.d = Standard error of differences of means, L.s.d = Least significant differences of means and Gm = Grand mean.

The variation of crop coefficient K_c across berry development stages is similar to crop evapotranspiration, small at early stage of berry development, then increasing to maximum at mid stage and decreasing at late stage (Fig. 2.7).

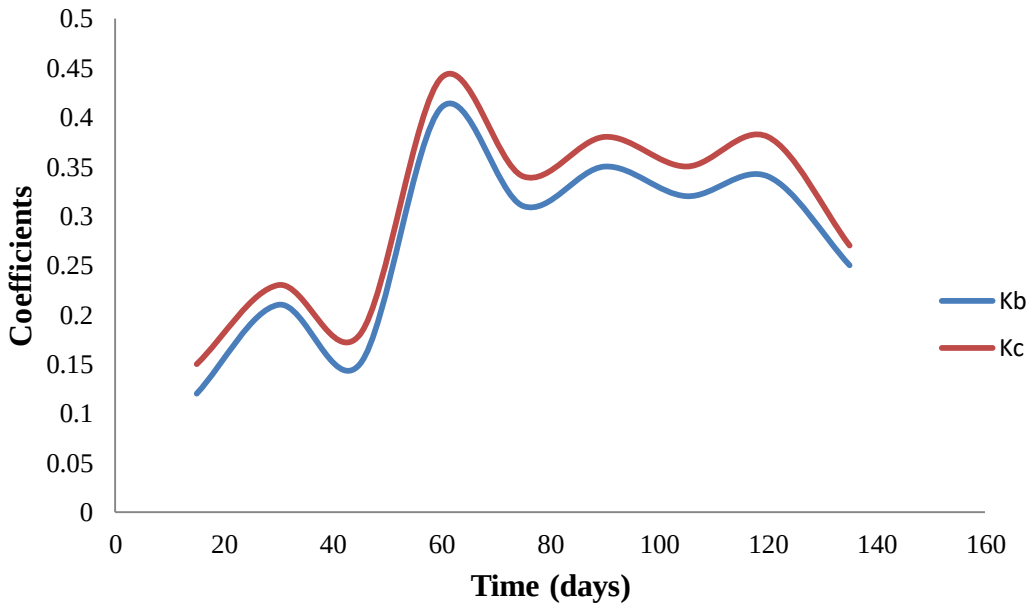

Figure 2.7: Variation of coefficients in a season

The vines were irrigated for 135 days in each season, which means 4.30 mm of water per day corresponds to 581 mm per season for full irrigation. In Marlborough District in New Zealand a report on Water productivity of vines recommended 355 mm of water for deficit irrigation per season and 646 mm of water per season for full irrigation (MWRC, 2007).

2.5 Conclusion

Grapevine seasonal daily mean evapotranspiration (ET_c) per vine for cv. 'Makutupora red' was 4.30 mm/day (583 mm/season) and the daily mean crop coefficients (K_c) for cv. 'Makutupora red' was 0.31. The vine evapotranspiration ET_c and the crop coefficient K_c vary with berry development stages. At initial stage mean daily ET_c was 2.70 mm/day

and K_c was 0.2 (for about 45 days), at mid stage ET_c was 5.30 mm/day and K_c was 0.38 (for 75 days) and at final stage ET_c was 4.96 mm/day and K_c was 0.27 (15 days).

For drip irrigation system the difference between crop and basal coefficient is small due to reduced water losses through evaporation. For other irrigation method the crop coefficient will be higher than in drip system due to the increase of evaporation coefficient (K_e). Cultivar 'Makutupora red' vines consume more water during mid-stage when the canopy is fully developed but consume less at initial stage and when fruits begin to ripen about one month before harvesting.

In this study it was found that the cultivar 'Makutupora red' requires only 4.30 mm of water per day and is concluded to be a very drought tolerant cultivar which is suitable to be grown in semi-arid areas.

2.6 Recommendations

The use of mean daily evapotranspiration (ET_c) per vine for *Vitis vinifera* cv. 'Makutupora red' of 4.30 mm/day is recommended, however, the schedule of irrigation must be followed according to ET_c values where at bud break to fruit set stage, low amounts of water applications are needed and in the following stages the vines consume more water due to an increase in the canopy size (architecture). For growers who can calculate ET_o, for full drip irrigation we recommend the use of crop coefficient of 0.14 at the first fifteen days and then increasing to 0.20 for the following 15 days to 30^{th} day. Then can be linearly increased to 0.38 in thirty days to 60^{th} day. Thereafter it can be maintained at 0.38 for 60 days to 120^{th} day, and then decreased to 0.27 for 15 days to 135^{th} day from pruning day. After that the water application is stopped to allow the grapes to ripe for harvesting and this is important for controlling diseases that attack the fruits

when the moisture is high. This is because at this stage the fruit become soft and more venerable to fungal diseases.

Using sap flow sensors and soil moisture probes for measuring crop water consumption (ET_c) have been found to be a convenient method for measuring transpiration and can measure ET_c for many plants at a time up to 40 if a multiplexer is used.

The crop coefficient values obtained are for cultivar *Vitis vinifera* L. 'Makutupora red'. Further investigation on water requirement for other cultivars grown in Dodoma is recommended due to their variation in water consumption and also for the application of deficit drip irrigation for quality improvement.

In this study it was assumed that the amount of transpiration from the evaporating soil layer is small and can be ignored. Allen *et al.* (1998) found that for shallow rooted crops, with depth of the maximum rooting zone less than 0.5 m, transpiration was negligibly small. It should also be noted that compensation heat pulse method for measuring transpiration is only 95% accurate compared to lysimeters (Green, 2009).

For non-drip irrigation method, ET_e must be adjusted to compensate for extra evaporation losses due to an increase of wetted and exposed surface area per plant (For drip irrigation system and cv. 'Makutupora red' mean daily transpiration ET_b = 3.91 mm/day and mean daily evaporation ET_e = 0.38 mm/day).

2.7 References

Allen, R., Pereira, S., Raes, D. and Smith, M. (1998). *Crop Evapotranspiration: Guidelines For Computing Crop Requirements*. Irrigation and Drainage Paper No. 56. Food and Agriculture Organization, Rome, Italy. 300pp.

Cassel, D. and Klute, A. (1986). Water Potential; Tensiometry In: *Methods of Soil Analysis Part 1. Physical and Mineralogical Methods.* (Edited by Klute, A.), American Society of Agronomy, Madison, Wisconsin, USA. pp. 563 – 594.

CETAWICO (2010). *Annual Company Progress Report.* Cantina di Sociale, Hombolo Township, Dodoma, Tanzania. 10pp.

Elgendy, R., Shaker, G. and Ahmed, O. (2012). Effect of foliar spraying with gibberellic acid and/or sitofex on bud behavior, vegetative growth, yield and cluster quality of Thompson Seedless grapevines. *Journal of American Science* 8(5): 21 – 34.

Er-Raki, S., Rodriguez, J., Garatuza-Payanc, J., Watts, C. and Chehbouni, A. (2013). Determination of crop evapotranspiration of table grapes in a semi-arid region of Northwest Mexico using multi-spectral vegetation index . *Journal of Agricultural Water Management* 122: 12 – 19.

Gardner, W. H. (1986). Water Content. In: *Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods*. (Edited by Klute, A.), American Society of Agronomy, Madison, Wisconsin, USA. pp. 493 – 544.

GENSTAT (2011). *Introduction to 13 for Windows Manual.* Statistical Services Centre, University of Reading, United Kingdom. 39pp.

Ginger, B. and Keefer, T. (2008). Comparison of field performance of multiple soil moisture sensors in a semi-arid rangeland. *Journal of the American Water Resources Association* 44(1): 121 – 135.

Green, S. (2009). *Measurements of Sap Flow by the Heat-Pulse Method. An Instruction Manual for the HPV system*. Palmerston North, New Zeland. 50pp.

Green, S., Clothier, B. and Deurer, M. (2007). Measuring and modeling stress response of grapevines to soil-water deficits. In: *Understanding and Modeling Water Stress Effects on Plant Growth Processes.* (Edited by Davidson, P.), The Horticulture and Food Research Institute of New Zealand Ltd., New Zealand. pp. 357 – 385.

Green, S., Clothier, B. and Jardine, B. (2003). Theory and practical application of heat-pulse to measure sap flow. *Agronomy Journal* 5:1371 – 1379.

Greer, H., Weston C. and Weedon, M. (2010). Shoot architecture, growth and development dynamics of *Vitis vinifera* cv. 'Semillon' grown in an irrigated vineyard with and without shade covering. *Functional Plant Biology* 37: 1061 – 1070.

Hussein, S. (2010). Value chain analysis of grapes in Tanzania. Dissertation for Award of MSc Degree at Sokoine University of Agriculture, Morogoro, Tanzania, 124pp.

Kose, B. (2014). Effect of light Intensity and temperature on growth and quality parameters of grafted vines. *Romanian Journal of Agricultural Sciences and Veterinary Medicene* 42(2): 507 – 515.

Lorenz, D., Eichhorn, K., Bleiholder, H., Klose, M. and Weber, E. (1995). Phenological growth stages of the grapevine, *Vitis vinifera* L. ssp. vinifera. Codes and descriptions according to the extended BBCH scale. *Australian Journal of Grape Wine Research* 1: 100 –103.

Lwelamira, J., Safari, J. and Wambura, P. (2015). Grapevine Farming and its Contribution to household income and Welfare among mallholder Farmers in Dodoma Urban District, Tanzania. *American Journal of Agriculture and Forestry* 3(3): 73 – 79.

Mahinda, A. (2014). Effect of drip irrigation on the production and economic returns of soghurm in semi arid areas of Tanzania. Dissertation for Award of MSc Degree at University of Nairobi, Nairobi, Kenya, 94pp.

Mahoo, H., Young, M. and Mzirai, B. (1999). Rainfall Variability and its Implications for the transferability of experimental results in the semi arid areas of Tanzania. *Tanzania Journal of Agricultural Science* 2: 127 – 140.

Marshall, D. (1958). Measurement of sap flow in conifers by heat transport. *Plant Physiology* 33: 385 – 396.

Medrano, H., Tomas, M. and Martorell, S. (2015). Improving Water productivity of vineyards in semi-arid regions. *Agronomy Sustainable Development* 35(2): 499 – 519.

Mercker, D. F. (2011). *User Manual for Continuous Logging Probe.* Software Solution, Cape Town, South Africa. 20pp.

Mrosso, L. (2007). Development of vineyard cultivation in Dodoma. *Proceedings of Central Zone Agricultural Research Steering Committee Meeting*. Dodoma, Tanzania, 23 May, 2007. 14pp.

Msongaleli, B. (2015). Assessment of the impacts of climate variability and change on rainfed cereal crop productivity in central Tanzania. Thesis for Award of PhD dgree at Sokoine University of Agriculture, Morogoro, Tanzania, 172pp.

MWRC (2007). *Marlborough Wine Research Centre Final Report on Vine Water Requirement.*Sustainable Farming Fund No.143. Marlborough, New Zealand. 19pp.

NIIR (2004). Integrated Development of Fruits. In: *Cultivation of Fruits, Vegetables and Floriculture.* (Edited by Gupta, K.), National Institute of Industrial Research, Delhi, India. pp. 115 – 122.

Prichard, T. (2001). Wine grape irrigation scheduling using deficit irrigation techniques. Universit of Calfornia, California, USA. [ucanr.edu/sites/ce_san_joaquin/ files/35706] site visted on 14/6/2013.

Rees, S. and Doyle, R. (2010). Effect of soil properties on Pinot Noir vine vigour and root distribution in Tasmanian vineyards. In: *19th World Congress of Soil Science, Soil Solutions for a Changing World*. 1- 6 August 2010, Tasmania. pp. 41 – 43.

Rwebugisa, R. (2008). Ground water recharge assessment in the Makutupora basin, Dodoma Tanzania. Dissertation for the Award of Masters Degree at International Institute for Geo-Information Science and Earth Observation, Enschede, Netherlands, 111pp.

Stern, R., Buysse, W. and Coe, R. (2004). *GenStat Discovery Edition for Everyday Use*. International Centre for Research in Agroforestry, Nairobi, Kenya. 114pp.

Suvocarev, K., Blanco, O., Faci, J. and Medina, E. (2013). Transpiration of table grape (*Vitis vinifera* L.) trained on an overhead trellis system under netting. *Journal of Irrigation Science* 31: 1289 – 1302.

Teixeira, A., Bastiaanssen, W. and Bassoi, L. (2007). Crop water parameters of irrigated wine and table grapes to support water productivity analysis in the Sa˜o Francisco river basin. *Agricultural Water Management* 94: 31 – 42.

TMA (2013). Weather forecast. from Tanzania meteorological agency certified in aeronautical meteorological services. [http://www.meteo.go.tz/index.php] site visited on 10/11/2013.

Williams, L. E. (2012). Effects of applied water amounts at various fractions of evapotranspiration (ETc) on leaf gas exchange of (cv. ‘Thompson seedless’} grapevines. *Australian Journal of Grape and Wine Research* 18: 100–108.

Zerizghy, G. and Rensburg, L. (2013). Comparison of neutron scattering and DFM capacitance instruments in measuring soil water evaporation. *Water South Africa* 39(2): 25 – 38.

Zhang, Y., Kang, S., Ward, E., Ding, R., Zhang, X. and Zheng, R. (2011). Evapotranspiration components determined by sap flow and microlysimetry techniques of a vineyard in northwest China: Dynamics and influential factors. *American Journal of Agricultural Water Management* 98: 1207 – 1214.

CHAPTER THREE

3.0 YIELD AND QUALITY RESPONSE OF GRAPES (*Vitis vinifera* L. cv. 'Makutopora red') TO DEFICIT IRRIGATION IN DODOMA, TANZANIA

Abstract

Crop water requirement of the vines were determined by compensation heat pulse method. Thereafter the vines were subjected to different irrigation regimes in order to study their effects to grape yield and quality. Three different drip irrigation methods namely conventional drip irrigation (CDI), partial root zone drying (PRD) and root zone deficit rationing (RDR) together with four irrigation levels of water at 100% of ET_c, 63.5% of ET_c, 56.3% ET_c and 48.9% of ET_c were interacted in a split plot experimental design with two factors (irrigation methods and irrigation levels) in order to determine a combination that would give optimum yield and good quality of grapes. Average yield per vine at 100% of ETc was 6.39 kg/vine and was decreased to 4.92 kg/vine at 63,5% of ETc, which was a decrease in yield by 23%. However grape quality was improved from 19 °Brix in full irrigated vines at 100% of ETc to 23°Brix at 63.5% of ETc irrigated grapes. Conventional deficit irrigation at 63.5% of ETc was observed to be the optimal option with grape yield of 5.39 kg/vine and grape quality at 22 °Brix. Conventional irrigation method at 56.3% of crop evapotranspiration was found to be a good option for grapes of very high quality, with total soluble solids at 24°Brix but with a decreased grape yield of 4.49 kg/vine. The results showed that a decrease in the amount of water applied to the vines by 36.5 % caused an improvement in grape quality but a decrease in grape yield by 23%. CDI with moderate water deficit application was observed to be the best option for optimum grape yield and high grape quality at 63.5% of ET_c.

Key words: Grape yield, grape quality, deficit irrigation.

3.1 Introduction

Vineyards in Tanzania are located in Dodoma Region which is characterized by long dry season (Mahoo *et al.*,1999). Grapes are harvested twice a year (Hussein, 2010), the first harvest is in the rainy season (February- March) and the second harvest in the dry season (August- September) (Hussein, 2010; Lwelamira *et al.*, 2015). Grape quality (normally total soluble solids are below 20°Brix) is low in the rainy season (Mroso, 2007; CETAWICO, 2010; Hussein, 2010; Lwelamira *et al.*, 2015) due to high night temperatures, high air humidity and frequent occurrence of diseases (Mori, 2005; Kose, 2014). The grapes harvested in the dry season have high quality (normally total soluble solids are over 22°Brix) due to low humidity, cool night temperature and reduced occurrence of diseases (Luscher *et al.*, 2016). However, the productivity is still low (2.5 Mg/ha) (Hussein, 2010). In the rain season vintage grape growers are advised to manage a health vine canopy and possibly to remove all or leave few grape clusters from the vines for keeping the plants strong and with sufficient reserves for the coming long dry season vintage (Mrosso, 2007). Usually in hot tropical regions, vines are pruned twice but only one crop is harvested (Shikhamany *et al.*, 2000).

Dodoma Region is semi-arid and there are very limited sources of irrigation water (Mahoo *et al.*, 1999; Mahinda, 2014; Lwelamira *et al.*, 2015; Msongaleli, 2015). About 90% of vineyards are rain fed and are grown in depressions or low land areas where the water table is high or the residual soil moisture is sufficient to support vines survival in the long dry season (Hussein, 2010). Soils of Dodoma mostly sand loam to sand clay loam have good drainage characteristics (Hussein, 2010; Mahinda, 2014; Msongaleli, 2015) and are suitable for grape production (Borghezan *et al.*, 2014). The major problem is inadequate availability of water for domestic and agricultural uses (Msongaleli, 2015). Recent geological surveys showed there is sufficient reserve of ground water in some

parts of Dodoma that if exploited can reduce the water inadequacy for both domestic and agricultural needs (Rwebugisa, 2008).

Drip irrigation is appropriate in arid and semiarid areas due to scarcity of water and high rate of evapotranspiration (Abdrabbo and Abou, 2009). The drip irrigation systems apply water slowly to keep the soil moisture within the desired range for plant growth (Chaves *et al.,* 2010). Therefore, conventional losses such as deep percolation, runoff and soil water evaporation are minimized (Franken, 2005). Drip irrigation under good management can achieve up to 95% water application efficiency (Payero *et al.*, 2008). Insect, diseases and fungus problem are proven to be reduced by not wetting the plant leaves. Apart from its ability to give high yield, drip irrigation helps to control weeds and reduce soil crusting (Lamm and Trooine, 2003). Due to high rate of evaporation in the dry season, drip irrigation system is superior over other systems and if used effectively it can provide the best means of serving water for grape production (Payero *et al.*, 2008). It has been observed that with irrigation, grape yield can be increased to between 8 and 15 Mg/ha (Mrosso, 2007). However, despite the increase in yield, there has been a decrease in grape quality (CETAWICO, 2010). Therefore, irrigation may increase grape yield (Santos *et al.,* 2007) but may also decrease grape quality (Castellarin *et al.,* 2015). The use of deficit irrigation is a solution to maintain grape quality and guarantee plant survival (Green *et al.,* 2003; Chalmers, 2007; Lopez *et al.,* 2009; Chaves *et al.,* 2010; Ozden *et al.,* 2010). Deficit irrigation is a reduced application of irrigation water below crop water requirement (ET_c) to vines between some stages of fruit and canopy development to control grapevine shoot growth with the aim of improving grape quality (Chaves *et al.,* 2007; Blum, 2009).

Conventional deficit irrigation (CDI) and partial root zone drying (PRD) have been used in regulating irrigation regimes that is the amount of water applied and the pattern of water application to the plant (Chaves *et al.*, 2010). Garcia *et al.* (2012) in Spain found that grape quality and yield were optimal when using irrigation level at 60% of ET_c (crop potential evapotranspiration). Ozden *et al.*, 2010 used irrigation level between 50% and 25% of Et_c hant found that irrigation level below 25% lowers the yield and quality of grapes cv. 'Shiraz'. Stressing plants by controlling water application for manipulating vegetative growth and berry composition has shown to produce inconsistence outcomes among grapevine cultivars (Chaves *et al.*, 2010).

More than 90% of grapevines in Dodoma belong to the local variety *Vitis vinifera* L. cv. 'Makutupora red'. It is a drought tolerant, long maturing, deeply red colored, highly acidic before ripening and high sugar content variety if allowed to ripe properly (CETAWICO, 2010). Under irrigation the variety takes about 175 days to reach full ripening under Dodoma environment (Mrosso, 2007). Apart from cutting off the water application one month before harvest, grape growers don't use planned deficit irrigation although in many cases vines are water stressed because of water scarcity and not for the purpose of achieving particular grape quality levels (Mrosso, 2007).

3.1.1 Irrigation regimes

Manipulation of irrigation regimes determines how, when and how much water is applied to the vines. Full irrigation that meets evapotranspiration demand has shown unfavourable effect to wine quality but with a moderate restriction of water availability to the plants it has proved to be beneficial for berry and wine composition. The effects of water restriction (deficit) reduce vegetative growth leading to improved canopy microclimate (Romero *et al.*, 2016) and carbohydrate partitioning to ripening berries and

smaller berry size leading to higher relative amounts of skin and seed in harvested fruit (Roby and Matthews, 2004), thereby positively affecting colour and flavour extraction into wine (Chalmers *et al.*, 2010). Deficit irrigation has been practiced in different ways to control grape and wine attributes (Koundouras *et al.*, 2013; Chorti *et al.*, 2016). Its effect largely depends on the timing, duration and intensity of the stress. Conventional deficit (DI), sustained deficit (SDI), regulated deficit (RDI) and partial root zone drying (PRD) are some of irrigation methods that have been used to manage the water regimes in the vineyards to achieve better grape and wine attributes (Chalmers, 2007). Green *et al.* (2007) got good results of grape quality and yield by using irrigation levels between 50% and 30% of ET_c on cv. 'Sauvignon blanc'**.** Conventional deficit irrigation (CDI) and partial root zone drying (PRD have been mostly used and have showed different results depending on the location and cultivar (García *et al.*, 2012).

3.1.2 Grape yield and quality

For 5 to 35 years old vines, grape yields remain the same if the vines are subjected to similar management and field conditions (Mrosso, 2007). Average yield per ha in Dodoma is 2.5 Mg in rain fed vineyards and 8 to 15 Mg in irrigated fields. In other grape growing countries yield per ha has been reported to be 5.4 Mg in Spain, 16 Mg in China and 17.5 Mg in USA (Lwelamira, 2015). In Dodoma, grapes (cv. 'Makutupora Red') are harvested for wine processing when total soluble solids reach 22˚Brix with grape juice pH ranging between 3.3 and 3.6 and titratable acids ranging between 4 and 7 g/l (Mrosso, 2007).

Wine consumers are also interested in phenols and anthocyanins compounds which are responsible for wine taste, mouth feel and color. It has also been reported that these compounds have health advantages and act as antioxidants (Tiisekwa, 1998;

Chaves *et al.,* 2010). Total phenol compounds were found to range between 200 and 425 mg/*l* and total anthocyanins from 50 mg/*l* to 200 mg/*l* from 14 cultivars of grapes studied in USA by Yang *et al.* (2009). The impact of water deficit stress on vine shoot growth, berry weight, grape composition and overall vintage quality investigated in Bordeaux vineyards showed that water deficit stress caused shoot growth slackening, limited berry weight and enhanced berry anthocyanin content and sugar content was greatest when water deficit was mild. Vine phenology and grape ripening are highly depending on water uptake conditions. It was also found that red grapes responded positively to water stress with an improvement in grape quality (Pieri and Gaudilere, 2005; Leeuwen *et al.,* 2009).

Therefore, investigation on the response of grape cv. 'Makutupora Red' to irrigation regimes is necessary for getting a better understanding of water rations and irrigation methods that will provide optimum grape yield and quality. The objective of this study was to investigate the effect of different irrigation regimes on yield and quality of grapes cv. 'Makutopora red'.

3.2 Materials and Methods

3.2.1 Description of the study area and the plant material

The study was carried out in Dodoma at Makutupora Agricultural Research Institute (ARI-Makutupora) which is located at latitude 5°58′669″ S and longitude 35^{0}46′093″ E about 26 km North of Dodoma Municipality. The area lies at an altitude of 1 050 m above sea level (Mahinda, 2014). The annual rainfall at ARI Makutupora ranges from 530 mm to 660 mm with rains falling between December and April. May to November is a dry season. The average annual air humidity is 65%, whereas average minimum and maximum daily temperatures are 15 and 32 ^{O}C. Sunshine hours are almost 12 per day,

with wind speed ranges between 1.0 m/s in February and 4m/s in October (Hussein, 2010).

3.2.2 Plant material and crop management

The plant material was V*itis vinifera* L. cv. 'Makutupora red' planted in 2002 on 0.4 ha at ARI-Makutupora at a spacing of 1.5 m within a row and 2.5 between rows. The vine yard plant population was 2667 vines/ha (10 000/3.75). The rows were situated in East-West orientation (this arrangement is important for maximum exposure of vine leaves to the sun light energy) with the sun overhead at noon (Mrosso, 2007). Part of the vine yard of 0.2 ha was subdivided into sub-plots. The number of plants in each sub-plot was nine (7.5 m x 4.5 m). During the trial the vines were thoroughly managed with timely manure addition, weed control, pruning, pest control, de-suckering and pest and vermin control. The vines were trained to bilateral cordons trellis (extension of trunk horizontally to Eastern and Western side) at 1 m above the ground and in each season were pruned to three bud spurs.

3.2.3 Water use determination

Vitis vinifera L. cv. 'Makutupora red' water consumption (transpiration) was measured during two growing seasons (2014–2015). Vines were irrigated using drip irrigation system. Compensation heat pulse method (6 x 2 channels) was used to determine vines daily water consumption per plant from pruning to fruit maturity. Instruments used were a set of sap flow sensors with CR 1000 data logger as explained by Green (2009). Water lost through evaporation per plant was also determined on daily basis by using soil moisture probes as explained by FAO (2000) and the user guideline for continuous logging probe (Mercker, 2011; Zerizghy and Rensburg, 2013).

The daily water use per vine was determined from readings taken from the full irrigated vines and was used for getting daily water application for irrigation levels V1 (100% of ETc), V2 (63.5% of ETc), V3 (56.3% of ETc) and V4 (48.9% of ETc). The daily water applications are shown in Table 3.1 for season 2015 and the daily duration of irrigation water application for each irrigation level across berry development stages in season 2015 is shown in Table 3.2. For season 2014, the daily water applications are shown in Table 3.3 and the daily duration of irrigation water application for each irrigation level across berry development stages is shown in Table 3.4. Average daily transpiration was 3.88 mm in 2015 and 3.96 mm in 2014. The average daily evaporation was 0.40 mm in 2015 and 0.37 mm in 2014. In the first 45 days all vines were irrigated at potential evapotranspiration and thereafter were subjected to deficit irrigation. The vines at early stages of production cycle (after pruning) must receive sufficient water for enhancing health flower and berry development (Green *et al.,* 2003; Chalmers, 2007; Chaves, 2007; Ozden *et al.,* 2010). After 135 days from pruning the water application was cutoff when the berries had reached a ripening stage and had already developed colour and soft skin. Water cutoff during ripening stage is a common recent practice in red wine grape vineyards (El-Ansary *et al.,* 2005; Conceicao *et al.,* 2013) because it was found that in red grapes irrigation cutoff during ripening stage improved phenols and anthocyanin composition (high colour with low seed tannins) without significant loss in grape yield (Bautista-Ortín *et al*., 2006; Keller *et al.*, 2006; Biondi, 2007; Koundouras *et al.*, 2013; Hunter *et al*., 2014).

Table 3.1: Mean daily vine water application across berry development stages for season 2015

Berry development stage	Time days	ET_e mm/d	ET_b mm/d	V1 mm/d	V2 mm/d	V3 mm/d	V4 mm/d
Wool	0 - 15	0.42	1.43	1.84	1.84	1.84	1.84
Bud burst	15 - 30	0.25	2.86	3.11	3.11	3.11	3.11
Flowering	30 - 45	0.21	1.95	2.16	2.16	2.16	2.16
Fruit set	45 - 60	0.33	5.66	5.99	3.16	2.59	2.03
Berry enlargement	60 - 75	0.27	4.36	4.63	2.45	2.02	1.57
Beginning of berry touch	75 - 90	0.34	6.05	6.38	3.36	2.76	2.15
Berry touch	90 - 105	0.42	4.67	5.09	2.76	2.29	1.82
Beginning of veraison	105 - 120	0.63	4.95	5.57	3.10	2.61	2.11
Veraison	120 - 135	0.45	3.63	4.09	2.27	1.90	1.55
Grand mean		**0.37**	**3.95**	**4.31**	**2.69**	**2.37**	**2.03**

Where, ET_e, ET_b, V1, V2, V3 and V4 are in mm/ day. GM= Mean daily average water application per vine in mm, ET_e = Evaporation in mm/day, ET_b = Plant transpiration in mm/day, ET_c (crop evapotranspiration mm/day) = ET_e + ET_b, V1 = 100% of ET_c, V2 = 63.5% of ET_c, V3 = 56.3% of ET_c and V4 = 48.9% of ET_c.

Table 3.2: Daily irrigation duration across berry development stages for season 2015

Berry development stage	Time days	T1 minutes	T2 minutes	T3 minutes	T4 minutes
Wool	0 - 15	63	63	63	63
Bud burst	15 - 30	107	107	107	107
Flowering	30 - 45	75	75	75	75
Fruit set	45 - 60	207	109	89	70
Berry enlargement	60 - 75	160	85	70	54
Beginning of berry touch	75 - 90	220	116	95	74
Berry touch	90 - 105	176	95	79	63
Beginning of veraison	105 - 120	192	107	90	73
Veraison	120 - 135	141	78	66	53
Grand mean		**149**	**93**	**82**	**70**

Where; T1, T2, T3 and T4 are the daily irrigation water application duration in minutes for irrigation levels V1, V2, V3 and V4, respectively.

Table 3.3: Mean daily vine water application cross berry development stages for season 2014

Berry development stage	Time days	ET_e mm/day	ET_b mm/day	V1 mm/day	V2 mm/day	V3 mm/day	V4 mm/day
Wool	0 - 15	0.47	2.16	2.63	2.63	2.63	2.63
Bud burst	15 - 30	0.40	3.03	3.43	3.43	3.43	3.43
Flowering	30 - 45	0.40	2.57	2.97	2.97	2.97	2.97
Fruit set	45 - 60	0.39	4.92	5.31	2.85	2.37	1.87
Berry enlargement	60 - 75	0.49	4.25	4.74	2.61	2.18	1.77
Beginning of berry touch	75 - 90	0.41	3.74	4.16	2.29	1.91	1.54
Berry touch	90 - 105	0.30	4.63	4.92	2.62	2.15	1.69
Beginning of veraison	105 - 120	0.38	5.52	5.90	3.14	2.59	2.03
Veraison	120 - 135	0.34	4.10	4.43	2.39	1.97	1.57
Grand mean		**0.40**	**3.88**	**4.28**	**2.77**	**2.47**	**2.17**

Where; ET_e, ET_b, V1, V2, V3 and V4 are in mm/ day. GM= Daily average water application per vine in mm, ET_e = Evaporation in mm/day, ET_b = Plant transpiration in mm/day, ET_c (crop evapotranspiration mm/day) = ET_e + ET_b, V1 = 100% of ET_c, V2 = 63.5% of ET_c, V3 = 56.3% of ET_c and V4 = 48.9% of ET_c.

Table 3.4: Daily irrigation duration across berry development stages 2014

Berry development stage	Time days	T1 minutes	T2 minutes	T3 minutes	T4 minutes
Wool	0 - 15	91	91	91	91
Bud burst	15 - 30	118	118	118	118
Flowering	30 - 45	102	102	102	102
Fruit set	45 - 60	183	98	82	65
Berry enlargement	60 - 75	164	90	75	61
Beginning of berry touch	75 - 90	144	79	66	53
Berry touch	90 - 105	170	90	74	58
Beginning of veraison	105 - 120	204	108	89	70
Veraison	120 - 135	153	82	68	54
Grand mean		**148**	**96**	**85**	**75**

Where; T1, T2, T3 and T4 are the daily irrigation water application duration in minutes for irrigation levels V1, V2, V3 and V4, respectively.

3.2.4 Experimental design

The experiment was a split plot design with four replications (Appendix 3). The main factor was irrigation levels obtained by adding evaporation to the fractions of transpiration (ET_b) which were V1 (ET_e + 100% of ET_b), V2 (ET_e + 50% of ET_b), V3 (ET_e + 40% of ET_b) and V4 (ET_e + 30% of ET_b). The sub factor was irrigation methods M1 (conventional deficit irrigation-CDI), M2 (partial root zone drying-PRD) and M3 (root zone deficit rationing-RDR). Potential Transpiration (ET_b) and water lost through evaporation (ET_e) were determined by the compensation heat pulse method as explained

by Green (2009). Evaporation (as water lost to the atmosphere from the top layer of the soil) was predetermined by method explained by Mercker (2011). Referring irrigation levels to crop evapotranspiration (ET_c) V1 = 100% of ET_c, V2 = 63.5% of ET_c, V3 = 56.3% of ET_c and V4 = 48.9 of ET_c. The water rationing was applied starting at fruit set to fruit maturity (beginning of ripening). Ozden *et al.*, 2010 found that the quality of cv. 'Shiraz 'grapes was improved with irrigation levels between 25% and 50% of reference evapotranspiration. In the first experiment, vines were pruned on 8th May, 2014 and grapes were harvested on 22th September, 2014 and in the second experiment vines were pruned on 15th April, 2015 and were harvested on 28th August, 2015 (about 175 days from pruning of vines to harvest of grapes in each experiment). Ten farmers' vineyards under drip irrigation were also investigated for comparison with experimental results on grape yield, TSS in ^{o}Brix and the amount of water applied.

3.2.5 Yield and quality components

Data on yield components measured were grape yield/vine, berry size (diameter), berry weight, bunch weight (g), biomass (g) and leaf area index. Quality components data were total soluble solids, titratable acids, pH, malic acid, tartaric acid, total phenols and anthocyanins compounds.

i. Yield components

Samples of grape yield per vine were obtained by harvesting, weighing and dividing by three the weight of harvested grapes from three randomly selected plants in each subplot. Then five bunches were picked from the harvested grapes in each subplot, weighed and then divided by five to get the weight of one bunch. Thereafter, twenty berries were randomly selected from the harvested grapes in each subplot by method explained by Chaves *et al.* (2007). The berries were weighed and then divided by twenty to get weight of one berry. Then the same twenty berries were fully immersed in water in a measuring

jar and the increase of volume was immediately taken and divided by twenty to get the volume of one berry from which the berry diameter was determined because cv. 'Makutupora red' berries are spherical. The biomass per vine was determined by first oven drying the pruned material (from one vine in each subplot) for 48 hours at 75 ^{O}C and then weighing the dry matter. Leaf area index was determined first by randomly picking leaves from fully canopy developed vines 120 days after pruning (before the start of leave senescence) and then cutting the leaves into 377 circle plates of 3.75 cm diameter as one set. Ten sets were made in that way. One set was collected from the experimental plots and other nine sets were collected from other 'Makutupora Red' vine fields.

Then leaf plates were oven dried for 48 hours in the oven to get leaves' dry weight per unit area of the leaves (Equation 10). Then just after harvesting the grapes leaves were picked from one vine in each plot oven dried for 48 hours at 75 ^{O}C, weighed and then divided by the leaves' dry weight per unit area to get the leaf area index which is one half of the total leaf area per unit ground surface area (Equation 11).

$$\boldsymbol{L_{dw} = \frac{4M_d}{n\pi d^2}} \quad \text{(10)}$$

$$\boldsymbol{LAI = \frac{M_{vd}}{A * L_{dw}}} \quad \text{(11)}$$

Where; L_{dw} = leaf dry mass per unit area = LDMUA

M_d = Weight of n leaf plates

n = number of leaf circular plates in a set

d = diameter of a leaf plate

M_{vd} = vine leaves' dry weight

LAI = Leaf area index

A = Row spacing * plant spacing = 2.5 * 1.5 = 3.75

ii. Quality components

The grapes harvested from each subplot were crushed (desteming) and fermented for three months. Just after crushing, the samples were taken for determination of total soluble solids (^{O}Brix) by digital refractrometer (Refractrometro), titratable acids by titration with a dilute solution of NaOH (Elana, 2006) and pH by electronic pH meter (Lopez *et al.,* 2009). After fermentation the must was racked and the wine was bottled. Wine samples in bottles were sent to the laboratory for determination of malic acid and tartaric acid by titration as explained by Elana (2006), phenol compounds according to the method of Iland *et al.* (2000), total anthocyanins by the pH differential method described by Giusti and Wrolstad (2005) and alcohol content by distillation using the method as explained by Iland *et al.* (2000).

3.3 Data Analysis

Analysis of variance (ANOVA) was used to analyse yield and quality components of grapes harvested in the two seasons. The collected data were subjected to analysis of variance (ANOVA) using GENSTAT 13 (Stern *et al.,* 2004) based on a split-plot design. The test of significant differences of yield and quality components mean values across treatments were performed based on Duncan multiple range test at a probability value of $\leq 5\%$ ($P \leq 0.5$), which was important for selecting treatments that produced high quality grapes and optimum yield under deficit irrigation.

3.4 Results

3.4.1 Vine water use and water deficit application

The daily water use was determined from readings taken from the full irrigated vines and were used for getting daily water application for irrigation levels V1, V2, V3 and V4 (Table 3.5) and daily irrigation duration (Table 3.6).

Table 3.5: Mean daily water application across berry development stages

Berry development stage	Time	ET_e	ET_b	V1	V2	V3	V4
	days	mm/d	mm/d	mm/d	mm/d	mm/d	mm/d
Wool	0 - 15	**0.44**	**1.79**	**2.23**	**2.23**	**2.23**	**2.23**
Bud burst	15 - 30	**0.33**	**2.95**	**3.27**	**3.27**	**3.27**	**3.27**
Flowering	30 - 45	**0.30**	**2.26**	**2.57**	**2.57**	**2.57**	**2.57**
Fruit set	45 - 60	0.37	5.30	5.65	3.01	2.48	1.95
Berry enlargement	60 - 75	0.38	4.30	4.69	2.53	2.10	1.67
Beginning of berry touch	75 - 90	0.37	4.90	5.27	2.83	2.33	1.84
Berry touch	90 - 105	0.37	4.65	5.01	2.69	2.22	1.76
Beginning of veraison	105 - 120	0.50	5.23	5.74	3.12	2.60	2.08
Veraison	120 - 135	0.40	3.86	4.26	2.33	1.94	1.56
Grand mean		**0.38**	**3.91**	**4.30**	**2.73**	**2.42**	**2.10**

Where, ET_e, ET_b, V1, V2, V3 and V4 are in mm/ day. GM= Daily average water application per vine in mm, ET_e = Evaporation in mm/day, ET_b = Plant transpiration in mm/day, ET_c (crop evapotranspiration mm/day) = ET_e + ET_b, V1 = 100% of ET_c, V2 = 63.5% of ET_c, V3 = 56.3% of ET_c and V4 = 48.9% of ET_c.

Table 3.6: Daily irrigation duration across berry development stages

Berry development stage	Time	T1	T2	T3	T4
	days	minutes	minutes	minutes	minutes
Wool	0 - 15	**77**	**77**	**77**	**77**
Bud burst	15 - 30	**113**	**113**	**113**	**113**
Flowering	30 - 45	**89**	**89**	**89**	**89**
Fruit set	45 - 60	195	104	86	67
Berry enlargement	60 - 75	162	87	72	58
Beginning of berry touch	75 - 90	182	98	80	63
Berry touch	90 - 105	173	93	77	61
Beginning of veraison	105 - 120	198	108	90	72
Veraison	120 - 135	147	80	67	54
Grand mean		**148**	**94**	**83**	**72**

Where, T1, T2, T3 and T4 are the daily irrigation water application duration in minutes for irrigation levels V1, V2, V3 and V4, respectively,

In the first 45 days after pruning, irrigation water was applied at the same rate to all vines at 100% of ET_c (Table 3.5 and Table 3.6). This was done to avoid stressing the vines with water deficits at early stages of berry development which can cause yield reduction and negative effect to quality of grapes (Chaves *et al.,* 2010). Myburgh (2003) in South Africa found that water deficits between pruning and early flowering stage, reduce grape yield and quality significantly.

3.4.2 Grape yield components

The results for yield components included yield/vine in kg/vine, leaf area index, pruned mass in g, berry diameter in cm, berry weight in g, bunch weight in g and cluster number/vine. The leaf index was obtained by dividing the leaves dry mass per unit ground area/vine by the leaf dry mass per unit area in g/m^2(LDMUA) shown in Table 3.7. The LDMUA mean value obtained is approximately uniform for leaves of a fully developed vine canopy assuming that the leaf thickness of 'Makutupora red' is the same for all leaves at veraison just before senescence. The leaves area measurements were carefully taken before senescence to avoid the effect of shrinking of leaves when loosing turgidity during the drying process of the leaves. LDMUA is used to estimate the leaf area index if the dry mass of the pruned leaves per vine of is known.

Table 3.7: Leaf dry mass per unit area for cv. 'Makutupora Red'

Set	Number of plates	Plate Diameter (cm)	Area per plate (cm^2)	Dry mass of leaves (g)	dry mass per plate (g)	Leaf dry mass per unit area (LDMUA) (g/m^2)
1	377	3.75	11.045	31.18	0.083	74.88
2	377	3.75	11.045	30.40	0.081	73.01
3	377	3.75	11.045	30.26	0.080	72.67
4	377	3.75	11.045	32.11	0.085	77.12
5	377	3.75	11.045	30.00	0.080	72.05
6	377	3.75	11.045	31.46	0.083	75.56
7	377	3.75	11.045	29.81	0.079	71.59
8	377	3.75	11.045	30.98	0.082	74.40
9	377	3.75	11.045	29.89	0.079	71.78
10	377	3.75	11.045	30.20	0.080	72.53
Mean						**73.56**

The effect of irrigation levels (V1, V2, V3 and V4) on yield components are shown in Table 3.8.

Table 3.8: Effect of irrigation levels on yield components

Level	Yield* (kg/vine)	LAI* (m^2/m^2)	Pm* (g/vine)	Bd* (cm)	Bw* (g)	Cw* (g)	Cn*
V1	**6.39d**	1.03b	644.64c	0.992b	3.915c	303.0c	26c
V2	4.92c	0.91ba	476.39b	0.933a	3.479b	229.6b	25cb
V3	3.77b	0.81a	415.53a	0.923a	3.333ba	183.5a	24b
V4	**3.22a**	0.78a	392.44a	0.915a	3.232a	160.7a	22a
s.e.d	0.22	0.06	22.953	0.012	0.111	10.18	0.6
L.s.d	0.49	0.15	51.923	0.028	0.252	23.028	1.3

*Means of 24 samples of yield components across irrigation levels; In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means; L.s.d = Least significant differences of means, Yield = grape yield in kg/vine, LAI = Leaf area index, Pm = Dry pruned mass in g/vine, Bd = berry diameter in cm, Bw = Berry weight in g, Cw = Cluster weight in g and Cluster number/vine.

Table 3.9 and Table 3.10 show the effect of irrigation levels in 2014 and 2015 seasons, respectively. In both seasons, grape yield/vine was found to higher in treatments with full irrigation (V1). Almost all yield components were relatively higher in full irrigated treatments than in water stressed treatments showing that deficit irrigation caused reduction in grape yield. These results are similar to the ones found by Chalmers (2007); Green *et al.* (2007); Lopez *et al.* (2009); Yang *et al.* (2009); Chaves *et al.* (2010). Most of yield components were decreasing with water application deficits.

Table 3.9: Effect of irrigation levels on yield components in season 2014

Level	Yield* (kg/vine)	LAI* (m^2/m^2)	Pw* (g/vine)	Bd* (cm)	b w* (g)	Cw* (g)	Cn*
V1	**6.58c**	1.01b	617.0c	0.994c	3.88b	314.72c	**27c**
V2	4.55b	0.92ba	499.4b	0.923b	3.46a	220.13b	26cb
V3	3.52ba	0.80a	407.5a	0.906ba	3.26a	170.11ba	24ba
V4	3.03a	0.78a	386.6a	0.894a	3.14a	144.84a	$22a_a$
S.e.d	0.5	0.08	28.27	0.01	0.15	24.12	1
L.s.d	1.13	0.17	63.96	0.022	0.35	54.55	2

*Means of 12 samples of yield components across irrigation levels; In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05); S.e.d = Standard error of differences of means; L.s.d = Least significant differences of means; Gm = Grand mean; CV% = Coefficient of variation and Yield = grape yield in kg/vine, LAI = Leaf area index, Pm = Dry pruned mass in g/vine, Bd = berry diameter in cm, Bw = Berry weight in g, Cw = Cluster weight in g and Cn = Cluster number/vine.

Table 3.10: Effect of irrigation levels on yield components in season 2015

Level	Yield* (kg/vine)	LAI* (m^2/m^2)	Pm* (g/vine)	Bd* (cm)	Bw* (g)	Cw* (g)	Cn*
V1	**6.21d**	1.05b	672.2b	0.989b	3.95b	291.23c	26c
V2	5.05c	0.89ab	453.4a	0.944a	3.50a	239.12b	24cb
V3	4.01b	0.82a	423.6a	0.940a	3.41a	196.96a	23ba
V4	**3.41a**	0.78a	398.3a	0.936a	3.33a	176.65a	22a
S.e.d	0.25	0.08	44.14	0.021	0.13	12.46	1
L.s.d	0.56	0.18	99.85	0.048	0.29	28.19	2

*Means of 12 samples of yield components across irrigation levels; In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means; L.s.d = Least significant differences of means, Gm = Grand mean, Yield = grape yield in kg/vine, LAI = Leaf area index, Pm = Dry pruned mass/vine in g/vine, Bd = berry diameter in cm, Bw = Berry weight in g, Cw = Cluster weight in g, and Cn = Cluster number/vine.

The effect of irrigation methods on yield components is shown in Table 3.11. Yield components were higher in conventional drip irrigation method (CDI) than in partial root zone drying (PRD) and root zone deficit rationing (RDR). The uneven distribution of water in PRD and RDR were observed to have lower yields than in CDI because the sides receiving less water in PRD and RDR caused water stress to the roots that caused yield components to be relatively low.

Table 3.11: Effect of irrigation methods on yield components

Method	Yield* (kg/vine)	LAI* (m^2/m^2)	Pm * (g/vine)	Bd* (cm)	Bw* (g)	Cw* (g)	Cn *
M1	**5.04c**	0.94b	517.37b	0.958b	3.61b	241.46c	25b
M2	**4.17a**	0.82ba	457.54a	0.920a	3.30a	197.23a	23a
M3	4.51b	0.89ba	471.83ba	0.945b	3.56ab	218.98b	24ba
S.e.d	0.18	0.04	25.84	0.009	0.09	9.239	0.8
L.s.d	0.37	0.09	53.335	0.018	0.186	19.068	1.6

*Means of 32 samples of yield components across irrigation methods (treatments); In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means, L.s.d = Least significant differences of means; and Yield = grape yield in kg/vine, LAI = Leaf area index in sq meters, Pm = Dry pruned mass in g/vine, Bd = berry diameter in cm, Bw = Berry weight in g, Cw = Cluster weight in g and Cn = Cluster number/vine

In both seasons yield components when compared at the same irrigation levels were lower in partial root zone drying (M2) than in conventional deficit irrigation (M1) and root zone deficit rationing (M3) (Table 3.12 and Table 3.13).

Table 3.12: Effect of irrigation methods on yield components in season 2014

Method	Yield* (kg/vine)	LAI* (m^2/m^2)	Pw* (g/vine)	Bd* (cm)	Bw* (g)	Cw* (g)	Cn*
M1	5.16b	0.92a	507.4a	0.946b	3.51b	248.31c	26a
M2	**3.92a**	0.89a	457.3a	0.910a	3.16a	180.17a	24a
M3	4.34a	0.83a	468.3a	0.932ab	3.63b	208.88b	25a
S.e.d	0.23	0.06	35.18	0.013	0.15	10.83	1
L.s.d	0.48	0.11	72.62	0.028	0.31	22.35	3

*Means of 16 samples of yield components across irrigation methods; In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means; L.s.d = Least significant differences of means; Yield = grape yield in kg/vine, LAI = Leaf area index, Pm = Dry pruned mass/vine, Bd = berry diameter in cm, Bw = Berry weight in g, and Cw = Cluster weight in g and Cn = Cluster number/vine

These results can be explained as the effect of excessive water stress in one side in the root zone of PRD. In irrigation method M1 roots receive the same amount of water around the vine base. In M3 roots receive water in different proportions around the vine base and this protects roots from drying permanently from severe water stresses. In partial root zone drying (M2) one side of the plant were not receiving water for 14 days alternatively and this caused excessive stress to some roots and consequently a reduction in yield components (Chaves *et al.,* 2010).

Table 3.13: Effect of irrigation methods on yield components in season 2015

Method	Yield* (kg/vine)	LAI* (m^2/m^2)	Pm* (g/vine)	Bd* (cm)	Bw* (g)	Cw* (g)	Cn*
M1	4.92b	0.97b	527.38a	0.969b	3.72b	234.60a	25b
M2	**4.41a**	0.81a	457.83a	0.929a	3.44a	214.30a	23a
M3	4.68ab	0.88ab	475.39a	0.958b	3.49a	229.07a	24ab
S.e.d	0.23	0.06	36.52	0.01	0.11	13.64	1
L.s.d	0.47	0.11	75.38	0.021	0.22	28.16	2

*Means of 16 samples of yield components across irrigation methods In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means; L.s.d = Least significant differences of means; Gm = Grand mean; CV% = Coefficient of variation and Yield = grape yield in kg/vine, LAI = Leaf area index, Pm = Dry pruned mass in g/vine, Bd = berry diameter in cm, Bw = Berry weight in g, Cw = Cluster weight in g and Cn = Cluster number/vine.

Almost all yield components were relatively higher in full irrigated treatments (V1M1, V1M2 and V1M3) than in water stressed treatments showing that deficit irrigation caused reduction in grape yield (Table 3.14).

Table 3.14: Effect of irrigation regimes (treatments) on yield components

Regime	Yield * (kg/vine)	LAI* (m^2/m^2)	Pm* (g/vine)	Bd* (cm)	Bw* (g)	Cw* (g)	Cn*
V1M1	**6.84e**	**1.15d**	**737.38f**	**0.996fg**	**4.08d**	**324.09h**	**26d**
V2M1	5.39dc	0.99dcb	526.63cd	0.947edc	3.63c	259.61fe	26d
V3M1	4.49b	0.86cba	418.18ab	0.955ed	3.44bc	209.92dc	26d
V4M1	3.45a	0.76a	387.29ab	0.931edcb	3.31abc	172.21cba	21a
V1M2	**5.79d**	**0.89cba**	**556.95ed**	**0.967fe**	**3.59cb**	**274.23fg**	**25dc**
V2M2	4.50b	0.87cba	458.51cb	0.925dcb	3.38cb	199.53dcb	24dcb
V3M2	3.35a	0.80ba	457.80bc	0.905ba	3.23ba	164.20ba	22ba
V4M2	3.02a	0.72a	356.92a	0.881a	2.99a	150.96a	21a
V1M3	**6.55d**	**1.05dc**	**639.59e**	**1.010g**	**4.08d**	**310.61hg**	**26d**
V2M3	4.86cb	0.86cba	444.03abc	0.927dcb	3.43bc	229.74ed	24dcb
V3M3	3.45a	0.77a	370.61ab	0.909cba	3.33cba	176.48cba	23cba
V4M3	3.19a	0.87cba	433.09abc	0.932edcb	3.39cb	159.08a	24dcb
Gm	**4.57**	**0.88**	**482.25**	**0.94**	**3.49**	**219.22**	**24**
S.e.d	0.36	0.10	48.04	0.019	0.18	18.20	1.4
L.s.d	0.74	0.20	97.77	0.038	0.38	37.04	2.8
F-Test	0.54	0.232	0.059	0.150	0594	0.758	0.121
CV%	10.9	14.1	15.20	2.6	7.3	11.90	8.9

*Means of 8 samples of yield components across irrigation regimes (treatments); In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means, L.s.d = Least significant differences of means, Gm = Grand mean, CV% = Coefficient of variation, Yield = Grape yield in kg/vine, LAI = Leaf area index, Pm = Dry pruned mass in g/vine, Bd = Berry diameter in cm, Bw = Berry weight in g, Cw = Cluster weight in g and Cluster number/vine.

In both seasons, grape yield was highest in full conventional drip irrigated treatments (VIM1) and lowest in partial root zone drying treatment (V4M2) (Table 3.15 and Table 3.16). It was found that yield components in V2M1 were not significantly different from yield components in V1M2 and yield components in V3M1 were not significantly from yield components in V2M2, similarly yield components in V4M1 were not significantly different from yield components in V3M2. This meant that the effect of water deficit in reducing grape yield is more in PRD than in CDI treatments at the same irrigation level. Chaves *et al*., 2007 and Romero *et al*., 2016 found that in PRD vines are more water stressed than in CDI.

Table 3.15: Effect of irrigation regimes on yield components in season 2014

Regime	Yield* (kg/vine)	LAI* (m^2/m^2)	Pm* (g/vine)	Bd* (cm)	Bw* (g)	Cw* (g)	Cn*
V1M1	**7.25f**	1.13d	722.42e	0.998e	3.99dc	269.55f	27.00cb
V2M1	5.66de	0.94dcb	523.86dcb	0.938dc	3.56dcb	216.56ed	28.50c
V3M1	4.55dc	0.83ba	438.54cba	0.940dc	3.37b	181.69dc	26.00cb
V4M1	3.18ba	0.77ba	367.35ba	0.908cb	3.14ba	188.17ba	20.75a
V1M2	**5.62de**	0.85cba	592.89ed	0.979ed	3.50cd	239.30ed	25.75cb
V2M2	3.58cba	0.94dcba	506.83dcb	0.910cb	3.22ba	175.94cba	24.25cba
V3M2	2.98a	0.83ba	427.96cba	0.900cba	3.18ba	204.96ba	23.00ba
V4M2	**2.80a**	0.71a	353.10a	0.853a	2.73a	208.46a	21.25a
V1M3	**6.85fe**	1.07dc	731.64ed	1.007e	4.15d	266.02fe	26.50cb
V2M3	4.41dcb	0.88cba	471.69dcb	0.920cb	3.60dcb	285.97dcb	24.50cba
V3M3	3.02a	0.75ba	355.89a	0.878ba	3.23ba	200.71ba	23.25ba
V4M3	3.09a	0.86cba	439.36cba	0.923cb	3.55cb	164.03ba	24.50cba
Gm	4.42	0.87	494.29	0.93	3.44	216.78	24.60
S.e.d	0.23	0.12	86.619	0.024	0.29	36.84	2.17
L.s.d	0.47	0.24	176.94	0.049	0.59	75.60	4.41
F-Test	0.16	0.45	0.48	0.26	0.55	0.99	0.42
CV%	14.4	17.70	23.20	4.100	12.50	21.10	13.70

*Means of 4 samples of yield components across irrigation regimes (treatments); In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means; L.s.d = Least significant differences of means, Gm = Grand mean; CV% = Coefficient of variation, Yield = Grape yield in kg/vine, LAI = Leaf area index, Pm = Dry pruned mass in g/vine, Bd = Berry diameter in cm, Bw = Berry weight in g, Cw = Cluster weight in g and CN =Cluster number/vine

Table 3.16: Effect of irrigation regimes on yield components in season 2015

Regime	Yield* (kg/vine)	LAI* (m^2/m^2)	Pm* (g/vine)	Bd* (cm)	Bw* (g)	Cw* (g)	Cn*
V1M1	**6.43f**	1.18c	775.08d	0.995dc	4.2e	301.14e	26.00e
V2M1	5.13de	1.04cb	529.39cb	0.957cba	3.7dc	234.69dc	24.50edc
V3M1	4.44dcb	0.89ab	397.82cba	0.970dcb	3.5cba	201.66cba	26.00e
V4M1	3.71ba	0.75a	407.24cba	0.955cba	3.5cba	227.09ba	22.00cba
V1M2	**5.96fe**	0.92ab	543.25c	0.956cba	3.7dcb	217.47ed	25.00edc
V2M2	4.72dc	0.81a	439.71cba	0.940cba	3.5cba	223.40cb	24.25edc
V3M2	3.72ba	0.77a	487.63cba	0.910a	3.3cba	179.49ba	21.25ba
V4M2	**3.24a**	0.73a	360.73a	0.910a	3.3ba	161.60a	20.25a
V1M3	**6.26f**	1.03cb	698.36d	1.014d	4.0ed	270.59ed	25.75edc
V2M3	5.31de	0.83ab	391.04ba	0.935ba	3.3cba	195.81dc	22.75dcba
V3M3	3.88cba	0.78a	385.32ba	0.940cba	3.4cba	204.90cba	22.25cba
V4M3	3.28a	0.87ab	426.82cba	0.942cba	3.2a	179.03a	24.00edc
Gm	4.67	0.89	486.87	0.952	3.55	216.41	23.67
S.e.d	0.45	0.12	74.201	0.027	0.21	28.03	1.49
L.s.d	0.91	0.25	151.15	0.056	0.44	57.30	3.02
F-Test	0.94	0.33	0.074	0.36	0.68	0.079	0.08
CV%	13.8	17.9	21.2	3.000	8.40	21.1	8.80

*Means of 4 samples of yield components across irrigation regimes (treatments); In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means; L.s.d = Least significant differences of means, Gm = Grand mean; CV% = Coefficient of variation Yield = grape yield in kg/vine, LAI = Leaf area index, Pm = Dry pruned mass in g/vine, Bd = berry diameter in cm, Bw = Berry weight in g, Cw = Cluster weight in g and Cn = Cluster number/vine

3.4.3 Grape quality components

Most of quality components were increasing with water application deficits. Fully irrigated regimes recorded significantly low amounts of quality components than in regimes with deficits irrigation. Tartaric acid and malic acid did not significantly differ across irrigation levels and total titratable acids were slightly higher in fully irrigated grapes (Table 3.17).

Table 3.17: Effect of irrigation levels on quality components

	TSS (°Brix)	Alco (%)	TTA (g/*l*)	T/T	pH	Ma (g/*l*)	Tar (g/*l*)	Phenol (g/*l*)	Anth (mg/*l*)
V1	**20a**	11.6a	5.47b	3.62a	3.606b	0.1836b	0.188a	1.504a	216.07a
V2	23b	13.8b	5.63b	4.22b	3.534a	0.1669a	0.194a	2.114b	538.94b
V3	25c	14.76c	5.11a	4.89c	3.537a	0.1836b	0,1925a	2.42c	664.57c
V4	27d	16.14d	5.09a	5.32d	3.531a	0.1614a	0.187a	2.701d	778.02d
S.e.d	0.3	0.214	0.116	0.1	0.011	0.0028	0.004	0.028	11.116
L.s.d	0.8	0.483	0.262	0.227	0.026	0.0063	0.008	0.063	25.146

*Means of 24 samples of yield components across irrigation levels; In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means; L.s.d = Least significant differences of means; Gm = Grand mean; and TSS = Total soluble solids, TTA = Total titratable acidity in g/*l* in T/T = TSS/TTA, Alco = Alcohol in percentage, pH = Grape juice pH, Ma = Malic acid concentration in g/*l*, Tar = Tartaric acid concentration in g/l, Phenol = Phenol compound concentration in grape juice in g/*l* and Anth = Anthocyanins concentration in the grape juice in mg/*l*.

Table 3.18: Effect of irrigation levels on quality components in season 2014

	TSS* (°Brix)	Alco* (%)	T/T*	TTA* (g/*l*)	pH*	Ma* (g/*l*)	Tar* (g/*l*)	Phenol* (g/*l*)	Anth* (mg/*l*)
V1	**20a**	**11.8a**	3.65a	5.61b	3.60b	0.164a	0.180a	1.43a	227.93a
V2	23b	13.8b	4.08b	5.86b	3.50a	0.177b	0.202b	2.05b	561.84b
V3	25c	14.8c	5.06c	4.94a	3.49a	0.159a	0.170a	2.40c	699.20c
V4	27d	16.1c	5.31c	5.04a	3.51a	0.153a	0.178a	2.67d	826.65d
S.e.d	0.5	0.35	0.15	0.22	0.01	0.006	0.006	0.048	22.55
L.s.d	1.2	0.8	0.34	0.49	0.023	0.013	0.014	0.109	51.01

*Means of 12 samples of yield components across irrigation regimes (treatments); In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means; L.s.d = Least significant differences of means, Gm = Grand mean, TSS = Total soluble solids, TTA = Total titratable acidity in g/*l* in T/T = TSS/TTA, Alco = Alcohol in percentage, pH = Grape juice pH, Ma = Malic acid concentration in g/*l*, Tar = Tartaric acid concentration in g/l, Phenol = Phenol compound concentration in grape juice in g/*l* and Anth = Anthocyanins concentration in the grape juice in mg/*l*.

In both seasons, TSS, alcohol percent, phenols and anthocyanins were higher under deficit irrigation than in full irrigated treatments (Table 18 and Table 19). Grape juice pH was slightly higher in treatments with full irrigation (V1). This implies that the improvement in berry quality was caused by water deficits. Bindon *et al.* (2011); Terry and Kurtural,

2011; Zarrouk *et al*. (2012; Gamero *et al.* (2014); Genebra *et al.* (2014); Castellarin *et al.* *(*2015); Casassa *et al.* (2015) found similar results on grapes under deficit irrigation.

Table 3.19: Effect of irrigation levels on quality components in season 2015

	TSS* (°**Brix**)	Alco* (**%**)	TTA* (**g/*l***)	T/T*	pH* (**g/*l***)	Ma* (**g/*l***)	Tar* (**g/*l***)	Phenol* (**g/*l***)	Anth* (**mg/*l***)
V1	**19a**	**11.4a**	5.32a	3.53a	3.61b	0.203b	0.195a	1.57a	204.22a
V2	23b	13.9b	5.41a	4.36b	3.57ab	0.157a	0.185a	2.18b	516.05b
V3	25c	14.7c	5.29a	4.72c	3.58ab	0.202b	0.215b	2.44c	629.93c
V4	27d	16.1d	5.15a	5.34d	3.55a	0.170a	0.196a	2.73d	729.38d
S.e.d	0.6	0.37	0.15	0.1	0.023	0.006	0.006	0.052	17.29
L.s.d	1.3	0.84	0.34	0.22	0.051	0.014	0.014	0.118	36.12

*Means of 12 samples of yield components across irrigation regimes (treatments); In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means; L.s.d = Least significant differences of means, Gm = Grand mean, TSS = Total soluble solids, TTA = Total titratable acidity in g/*l* in T/T = TSS/TTA, Alco = Alcohol in percentage, pH = Grape juice pH, Ma = Malic acid concentration in g/*l*, Tar = Tartaric acid concentration in g/l, Phenol = Phenol compound concentration in grape juice in g/*l*, and Anth = Anthocyanins concentration in the grape juice in mg/*l*.

Quality components were lower in conventional drip irrigation method (CDI) than in partial root zone drying (PRD) and root zone deficit rationing (RDR). The uneven distribution of water in PRD and RDR had more deficit effect in the sides receiving less water which affected the roots that caused quality components to be relatively high except tartaric and malic acid that did not differ significantly across irrigation methods, total titratable acids was slightly lower in PRD (Table 3.20).

Table 3.20: Effect of irrigation methods on quality components

	TSS (°Brix)	Alco (%)	TTA (kg/vine)	T/T	pH	Ma (g/*l*)	Tar (g/*l*)	Phenol (g/*l*)	Anth (mg/*l*)
M1	23a	13.42a	5.4b	4.22a	3.54a	0.172a	0.183a	2.07a	503.08a
M2	**25c**	14.79c	5.02a	4.99b	3.56b	0.171a	0.185a	2.31c	600.76c
M3	24b	14.01b	5.56c	4.32a	3.55ab	0.176a	0.202b	2.17b	544.36b
S.e.d	0.1	0.079	0.067	0.06	0.008	0.005	0.004	0.013	5.839
L.s.d	0.3	0.163	0.137	0.12	0.016	0.009	0.008	0.027	12.052

*Means of 32 samples of yield components across irrigation methods (treatments). In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means; L.s.d = Least significant differences of means; Gm = Grand mean; and TSS = Total soluble solids, TTA = Total titratable acidity in g/*l* in T/T = TSS/TTA, Alco = Alcohol in percentage, pH = Grape juice pH, Ma = Malic acid concentration in g/*l*, Tar = Tartaric acid concentration in g/l, Phenol = Phenol compound concentration in grape juice in g/*l* and Anth = Anthocyanins concentration in the grape juice in mg/*l*.

Table 3.21: Effect of irrigation methods on quality components in season 2014

	TSS* (°Brix)	Alco* (%)	TTA* (g/*l*)	T/T*	pH*	Ma* (g/*l*)	Tar* (g/*l*)	Phenol* (g/*l*)	Anth* (mg/*l*)
M1	22a	13.4a	5.6c	4.02a	3.56a	0.184a	0.187a	2.11a	476.81a
M2	**25c**	14.7c	4.9a	4.39a	3.59b	0.187a	0.198ba	2.36c	565.20c
M3	24b	14.0b	5.4b	4.44a	3.58b	0.178a	0.208b	2.22b	517.61b
S.e.d	0.1	0.06	0.09	0.13	0.012	0.008	0.006	0.011	4.09
L.s.d	0.2	0.13	0.18	0.27	0.026	0.017	0.013	0.023	8.44

*Means of 16 samples of yield components across irrigation regimes (treatments); In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means; L.s.d = Least significant differences of means, Gm = Grand mean, TSS = Total soluble solids, TTA = Total titratable acidity in g/*l* in T/T = TSS/TTA, Alco = Alcohol in percentage, pH = Grape juice pH, Ma = Malic acid concentration in g/*l*, Tar = Tartaric acid concentration in g/l, Phenol = Phenol compound concentration in grape juice in g/*l* and Anth = Anthocyanins concentration in the grape juice in mg/*l*.

In both seasons (Table 3.21 and Table 3.22), the variations of TSS across irrigation method were higher with partial root zone drying than in convention deficit irrigation and root zone dry rationing methods. There was no significant difference in berry juice pH across irrigation levels and irrigation methods. Total titratable acid (TTA) was slightly higher in full irrigated treatments. Chalmers (2007) also found that the value of TTA was lower in grapes under deficit irrigation and was higher in fully irrigated grapes.

Table 3.22: Effect of irrigation methods on quality components in season 2015

	TSS* (°Brix)	Alco* (%)	TTA* (g/*l*)	T/T*	pH*	Ma* (g/*l*)	Tar* (g/*l*)	Phenol* (g/*l*)	Anth* (mg/*l*)
M1	23a	13.43a	5.2a	4.43a	3.53a	0.161a	0.179a	2.04a	529.28a
M2	**25c**	**14.88c**	5.1a	5.13b	3.53a	0.154a	0.173a	2.26c	636.32c
M3	24b	14.06b	5.7b	4.34a	3.52a	0.175b	0.196b	2.12b	571.11b
S.e.d	0.2	0.15	0.11	0.07	0.012	0.003	0.004	0.023	10.81
L.s.d	0.4	0.3	0.24	0.15	0.024	0.007	0.007	0.047	22.31

**Means of 16 samples of yield components across irrigation regimes (treatments); In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means; L.s.d = Least significant differences of means, Gm = Grand mean, TSS = Total soluble solids, TTA = Total titratable acidity in g/*l* in T/T = TSS/TTA, Alco = Alcohol in percentage, pH = Grape juice pH, Ma = Malic acid concentration in g/*l*, Tar = Tartaric acid concentration in g/l, Phenol = Phenol compound concentration in grape juice in g/*l* and Anth = Anthocyanins concentration in the grape juice in mg/*l*.

The effect of irrigation regimes on grape quality is shown in Table 3.23. The quality components in V2M1 were not significantly different from quality components in V1M2 and quality components in V3M1 were not significantly from quality components in V2M2, similarly quality components in V4M1 were not significantly from quality components in V3M2. This meant that what is achieved by PRD can be achieved in CDI by slightly increasing water deficit.

Table 3.23: Effect of irrigation regimes (treatments) on grape quality components

IR	TSS (°Brix)	Alco (%)	TTA (g/*l*)	T/T	pH	Ma (g/*l*)	Tar (g/*l*)	Phenol (g/*l*)	Anth (mg/*l*)
V1M1	**19a**	**11.0a**	3.38a	**5.6f**	3.61f	0.183cd	0.188c	**1.42a**	**185.1a**
V2M1	**22c**	**13.3c**	4.09c	**5.5ef**	3.52dcba	0.167abc	0.168a	**2.02c**	**500.0c**
V3M1	24e	14.2dc	4.44d	5.4ef	3.48ba	0.177bcd	0.189c	2.32f	625.4de
V4M1	25f	15.2fg	4.99ef	5.1bcd	3.51dcba	0.162ab	0.187c	2.52h	701.9f
V1M2	20b	11.9b	3.72b	5.4ef	3.61f	0.185d	0.189c	1.55b	230.6b
V2M2	24e	14.5e	4.84ef	5abc	3.51dcba	0.154a	0.171ab	2.22e	582.7d
V3M2	26g	15.5gh	5.51g	4.7a	3.47a	0.182cd	0.194c	2.55h	720.3fh
V4M2	**29i**	17.3i	5.89h	4.9abc	3.54ed	0.161ab	0.187c	2.92j	869.5g
V1M3	20b	11.8b	3.75b	5.4def	3.58fe	0.183cd	0.187c	1.54b	232.6b
V2M3	23d	13.7cd	3.73b	6.4g	3.47a	0.18cd	0.242d	2.11d	534.1c
V3M3	24e	14.6ef	4.72de	5.2bcde	3.53dc	0.182cd	0.194c	2.38g	648.1e
V4M3	**27h**	16.0h	5.10f	5.3cdef	3.49cba	0.161ab	0.186bc	2.67i	762.7h
Gm	**24**	**14.1**	**4.51**	**5.33**	**3.53**	**0.173**	**0.19**	**2.19**	**549.4**
S.e.d	0	0.3	0.14	0.2	0.02	0.008	0.074	0.04	14.65
L.s.d	1	0.5	0.29	0.3	0.04	0.016	0.015	0.07	30.33
F-Test	0	0	0.001	0.001	0.004	0.357	0.001	0	0.001
CV%	2	1.6	3.7	3.5	0,90	7.4	5.9	1.7	3.0

*Means of 8 samples of yield components across irrigation regimes (treatments); In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means; L.s.d = Least significant differences of means, Gm = Grand mean; CV% = Coefficient of variation, TSS = Total soluble solids, TTA = Total titratable acidity in g/*l* in T/T = TSS/TTA, Alco = Alcohol in percentage, pH = Grape juice pH, Ma = Malic acid concentration in g/*l*, Tar = Tartaric acid concentration in g/*l*, Phenol = Phenol compound concentration in grape juice in g/*l* and Anth = Anthocyanins concentration in the grape juice in mg/*l*.

Total soluble solids (TSS) were significantly lower in irrigation regimes VIMI, VIM2 and V1M3 than in water stressed treatments V2MI, V2M2, V2M3…..V4M3 in both seasons (Table 3.24 and Table 3.25). This indicated that the TSS was relatively higher in more stressed vines McCarthy (1997); Yang *et al.* (2009) and Hunter *et al.* (2014) also observed that grapes under deficit irrigation had a higher TSS than grapes under full irrigation.

Table 3.24: Effect of irrigation regimes on quality components in season 2014

	TSS* (°Brix)	Alco* (%)	TTA* (g/*l*)	T/T*	pH*	Tar* (g/*l*)	Phenol* (g/*l*)	Anth* (mg/*l*)
V1M1	**18a**	**11.0a**	5.5edc	**3.29a**	3.62ed	0.21fedc	**1.49a**	**180.7a**
V2M1	**22d**	**13.4c**	5.8e	**3.85b**	3.54ba	0.20edc	2.09d	483.4d
V3M1	24ed	14.1edc	5.7ed	4.15cb	3.55cba	0.22fedc	2.32gf	588.5f
V4M1	25gf	15.2gf	5.3dc	4.78d	3.53a	0.19dcb	2.52ih	654.9hg
V1M2	20cb	12.0b	5.3dc	3.78b	3.63e	0.24f	1.66cb	227.7cb
V2M2	24fe	14.4fed	4.8ba	5.10e	3.60edc	0.17ba	2.28fe	549.0fe
V3M2	26hg	15.4hg	4.7a	5.54f	3.58edcba	0.24f	2.57ji	677.2h
V4M2	**30i**	17.1i	4.8ba	6.11g	3.57dcba	0.19dcb	2.94k	807.0j
V1M3	19ba	11.3ba	5.2cb	3.66b	3.59edcb	0.23fe	1.57ba	204.2ba
V2M3	23ed	13.7dc	5.7ed	4.13cb	3.57dcba	0.16a	2.18ed	515.7ed
V3M3	25fe	14.6gfe	5.5edc	4.46dc	3.62ed	0.22fed	2.42hg	624.1gf
V4M3	**27h**	16.2h	5.3dc	5.13e	3.55cba	0.19cba	2.72j	726.3i
Gm	**23.6**	**14**	**5.3**	**4.5**	**3.58**	**0.2**	**2.23**	**519.9**
S.e.d	0.6	0.4	0.21	0.16	0.00	0.02	0.12	18.54
L.s.d	1.3	0.9	0.42	0.32	0.06	0.03	0.06	40.47
F-Test	0.001	0.001	0.004	0.001	0.041	0.001	0.001	0.001
CV%	1.4	1.3	4.6	4.6	1.0	12.6	1.4	2.2

*Means of 4 samples of yield components across irrigation regimes (treatments); In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means; L.s.d = Least significant differences of means, Gm = Grand mean; CV% = Coefficient of variation, TSS = Total soluble solids, TTA = Total titratable acidity in g/*l* in T/T = TSS/TTA, Alco = Alcohol in percentage, pH = Grape juice pH, Ma = Malic acid concentration in g/*l*, Tar = Tartaric acid concentration in g/l, Phenol = Phenol compound concentration in grape juice in g/*l* and Anth = Anthocyanins concentration in the grape juice in mg/*l*.

Table 3.25: Effect of irrigation regimes on quality components in season 2015

	TSS* (°Brix)	**Alco* (%)**	**TTA* (g/*l*)**	**T/T***	**pH***	**Ma* (g/*l*)**	**Tar* (g/*l*)**	**Phenol* (g/*l*)**	**Anth* (mg/*l*)**
V1M1	**20a**	**11.1a**	**5.7c**	**3.5ba**	3.6f	0.18b	0.20b	**1.4a**	**189a**
V2M1	23c	**13.1dc**	5.3cb	4.3c	3.5dcba	0.15a	0.17a	2.0c	517cd
V3M1	24cd	14.3e	5.2cba	4.7edc	3.5ba	0.16ba	0.18ba	2.3e	662fe
V4M1	25fe	15.2fe	4.8ba	5.2gf	3.5dcba	0.15a	0.17a	2.5f	749gh
V1M2	20ba	11.9ba	5.6c	3.7ba	3.6f	0.16ba	0.18ba	1.5ba	234ab
V2M2	24ed	14.5e	5.3cb	4.6dc	3.5dcba	0.16ba	0.18ba	2.2d	616fe
V3M2	26gf	15.7f	4.7a	5.5hg	3.5a	0.15a	0.17a	2.5fg	763gh
V4M2	**29h**	17.5g	5.0ba	5.7h	3.5ed	0.15a	0.17a	2.9h	932i
V1M3	21b	12.4cb	5.6c	3.8b	3.6fe	0.16ba	0.18ba	1.5ba	261b
V2M3	24dc	13.6de	7.0d	3.3a	3.5a	0.22c	0.25c	2.0c	553d
V3M3	25fe	14.5e	4.9ba	5.0fed	3.5dc	0.16ba	0.18ba	2.4e	672f
V4M3	**27g**	15.8f	5.2cba	5.1gfe	3.5cba	0.16ba	0.17a	2.6g	799h
G.m	**24**	**14.1**	**5.4**	**4.5**	**3.5**	**0.16**	**0.18**	**2.1**	**578.9**
S.e.d	0.6	0.43	0.3	0.2	0	0.01	0.01	0.1	38.6
L.s.d	1.3	0.9	0.6	0.5	0	0.02	0.03	0.1	59.6
F-Test	0.001	0.001	0.001	0.001	0.173	0.001	0.001	0.001	0.001
CV%	2.5	2.9	6	6.1	0.9	5.6	5.7	3	5.3

*Means of 4 samples of yield components across irrigation regimes (treatments); In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means; L.s.d = Least significant differences of means, Gm = Grand mean; CV% = Coefficient of variation, TSS = Total soluble solids, TTA = Total titratable acidity in g/*l* in T/T = TSS/TTA, Alco = Alcohol in percentage, pH = Grape juice pH, Ma = Malic acid concentration in g/*l*, Tar = Tartaric acid concentration in g/*l*, Phenol = Phenol compound concentration in grape juice in g/*l* and Anth = Anthocyanins concentration in the grape juice in mg/*l*.

Comparing experimental results and farmer's data (Table 3.26) it was observed that the farmer grape yields were higher than in rain fed vineyards but grape quality was relatively low although the amounts of water they were applying on average were not excessive. With the application of the same amount of water farmers can improve the grape quality by rectifying their irrigation schedules to match with the suggested rates of irrigation regimes V2M1 and V3M1which varies depending on berry stages.

Table 3.26: Farmers data for first season 2014 and second season 2015

Name	Season	Water amount (mm per week)	Harvest (kg/tree)	TSS (^{O}Brix)	pH
Zuzu vineyard	1	20.87	5.0	20.5	3.35
Dodep	1	20.00	5.4	19.0	3.32
Kenyunko	1	18.26	4.0	21.0	3.33
Mbise	1	18.26	4.5	20.5	3.38
Veyula Mission	1	20.00	5.5	20.0	3.35
Mwilu	1	19.13	4.5	20.5	3.35
Nyanda	1	13.04	3.5	22.0	3.42
Buigiri	1	20.87	5.0	21.4	3.34
Solanki	1	18.26	3.5	21.6	3.33
Mtenga	1	17.39	4,2	23.2	3.47
Zuzu vineyard	2	20.87	5.3	20.0	3.31
Dodep	2	20.00	5.4	19.5	3.33
Kenyunko	2	18.26	3.9	21.0	3.34
Mbise	2	18.26	4.0	21.0	3,33
Veyula mission	2	20.87	5.7	20.0	3.32
Mwilu	2	19.13	4.5	21.5	3.35
Nyanda	2	13.04	3.3	22.0	3.44
Buigiri	2	20.87	5.3	20.0	3.30
Solanki	2	18.26	3.8	21.3	3.30
Mtenga	2	17.39	4.5	22.3	3.37
Average		18.70	**4.6**	**20.9**	**3.35**

3.5 Conclusion

Deficit irrigation can improve most of quality components (TSS, alcohol percentage, concentration of grape phenol and anthocyanin compounds) but reduces yield components (grape yield, cluster weight, berry size, berry weight, pruned dry mass and leaf area index). The leaf area per unit mass of dried leaves (LDMUA) was found to be 73.56 g/m^2 for cv. 'Makutupora red' (leaf area Index is obtained by dividing oven dried pruned leaf mass per vine per ground area by LDMUA). The poor quality of grapes harvested from irrigated vineyards in Dodoma can be improved by using conventional irrigation method schedule at water deficit application rates between 56.3% and 63.5% of vine crop evapotranspiration. Moderate deficit irrigation proved to be the ideal irrigation practice for improving grape quality from, 19 °Brix of total soluble solids (TSS) in fully irrigated (FI) grapes to 23 °Brix in grapes under conventional drip deficit irrigation method (CDI) at 63.5% of ET_c, with a little decrease in yield from 18.24 Mg/ha (6.84 kg/vine) in grapes

under full irrigation (100% of ET_c) to 14.37 (5.39) Mg/ha in grapes under conventional drip deficit irrigation method (CDI) at 63.5% of ET_c which is a big increase in grape yield by 11.87 Mg/ha (4.45 kg/vine) as compared to 2.5 Mg/ha (0.94 kg/vine) in rain fed vineyards.

At the same irrigation level PRD and RDR produced higher grape quality but similar results were achieved by CDI by slightly increasing the water deficit. For instance, the grape quality and yield recorded in PRD at 63.5 of ET_c (TSS = 24 and yield = 4.50 kg/vine) did not differ significantly from those recorded in CDI at 56.3% of ET_c (TSS = 24°Brix and yield = 4.49 kg/vine). There was an improvement in grape quality in all irrigation regimes with deficit irrigation. Most of quality components increased with water deficits.

3.6 Recommendations

It is recommended that farmers in Dodoma should use an irrigation schedule for moderate deficit convention drip irrigation with water application between 63.5% and 56.3 % of ET_c for improving yield and quality of cv. ‘Makutupora red’. To achieve these results, the vines must be managed properly to control diseases and nutrients deficiencies such that the grape vines are purposely responding to water application rates, while assuming the effect of other factors on the vines are uniform or negligibly small. Use of deficit irrigation in other grape cultivars in Dodoma such as *Vitis vinifera* L. cultivars ‘Makutupora white’ ‘Chenin blanc’, ‘Black rose’ and ‘Ruby seedless’ will require further investigation to determine exactly the relation between water consumption and quality of grapes in order to quantify how much is gained in quality at the expense of loss in yield.

3.7 References

Abdrabbo, A. and Abou, K. (2009). Comparison among different irrigation systems for deficit irrigated corn in the Nile valley. *Agricultural Engineering International* 11: 122 – 138.

Bautista, A., Fernandez, J., Lopez, J. and Gomez, E. (2006). The effect of grape ripening stage on red wine color. *International Journal of Vine and Wine Sciences* 40: 15 – 24.

Bindon, K., Myburgh, P., Oberholster, A., Roux, K. and Du, C. (2011). Response of grape and wine phenolic composition in *Vitis vinifera*L. cv. 'merlot' to variation in grapevine water status. *South Africa Journal of Enology Viticulture* 32: 74 – 88.

Biondi, M. (2007). Dynamics of grape berry volume change during ripening. Thesis for Award of Master Degree at Washington State University, USA, 101pp.

Blum, A. (2009). Effective use of water and not water-use efficiency. *Annals of Applied Biology* 112: 119 – 123.

Borghezan, M., Villar, L., Silva, T., Canton, M., Guerra, M. and Campos, C. (2014). Phenology and vegetative growth in a new production region of grapevines: Case Study in São Joaquim, Santa Catarina, Southern Brazil. *Open Journal of Ecology* 4: 321 – 335.

Casassa, F., Keller, M. and Harbertson, J. (2015). Regulated deficit irrigation alters anthocyanins, tannins and sensory properties of cabernet sauvignon grapes and wines. *Molecules* 20: 7820 – 7844.

Castellarin, S., Gambetta, G., Wada, H., Krasnow, M., Grant R. Cramer, G. and Peterlunger, E. (2015). Characterization of major ripening events during softening ingrape: turgor, sugar accumulation, abscisic acid metabolism,colour development, and their relationship with growth. *Journal of Experimental Botany* 67: 709 – 722.

CETAWICO (2010). *Annual Company Progress Report.*Cantina di Sociale, Hombolo Township, Dodoma, Tanzania. 10pp.

Chalmers, Y. (2007). Influence of sustained deficit irrigation on physiology and phenolic compounds in wine grapes and wine. Dissertation for Award of PhD Degree at University of Adelaide, Adelaide, Australia, 200pp.

Chaves, M. M., Zarrouk, O., Francisco, R., Costa, J., Santos, T. and Regalado, A. P. (2010). Grapevine under deficit irrigation: hints from physiological and molecular data. *Annals of Botany* 105: 661 – 676.

Chaves, M., Santos, T., Souza, C., Ortun, M., Rodrigues, M. and Lopez, C. (2007). Deficit irrigation in grapevine improves water-use efficiency while controlling vigour and production quality. *Annals of Applied Biology* 150: 235 – 252.

Chorti, E., Kyraleou, M., Kallithraka, S., Pavlidis, M., Koundouras, S. and Kanakis, I. (2016). Irrigation and Leaf Removal Effects on Polyphenolic Content of Grapes and Wines Produced from cv. ‘Agiorgitiko’ (*Vitis vinifera* L.). *Notulae Botanicae Horti Agrobotanici* 44(1): 133 – 139.

Conceicao, M., Zepli, J. and Paula, M. (2013). Irrigation cutoff on 'BRS Clara' seedless grapevines during berry ripening stage. *Journal of Viticulture and Enology* 28(2): 167 – 170.

Elana, L. (2006). The evaluation of Fourier transform infrared spectroscopy for the determination of total phenolics and total anthocyanins concentrations of grapes. Dissertation for Award of MSc Degree at Stellenbosch University, South Africa., 162pp.

Franken, K. (2005). *Water Report 29 in Africa in Figures- Aquastat survey*. Food and Agricultural Organization of the United Nations, Rome, Italy.

Gamero, E., Moreno, D., Vilanova, M., Uriarte, D., Prieto, M. and Valdes, M. (2014). Effect of bunch thinning and water stress on chemical and sensory characteristics of Tempranillo wines. *Austrilian Journal of Grape Wine Research* 20: 394 – 400.

García, J., Cutillas, A. and Romero, P. (2012). Financial analysis of wine grape production using regulated deficit irrigation and partial-root zone drying strategies. *Journal of Irrigation Science* 30(3): 179 – 188.

Genebra, T., Santos, R., Francisco, R., Pinto, M., Brossa, R. and Serra, A. (2014). Proanthocyanidin accumulation and biosynthesis are modulated by the irrigation regime in tempranillo seeds.*International Journal of Molecolor Science* 15: 11862 – 11867.

GENSTAT (2011). *Introduction to 13 for Windows Manual.* Statistical Services Centre, United Kingdom. 39pp.

Giusti, M. M. and Wrolstad, R. E. (2005). Characterization and Measurement of Anthocyanins by Uv-visible Spectroscopy. In: *Handbook of Food Analytical Chemistry: Pigments, Colorants, Flavors, Texture And Bioactive Food Components.* (Edited by Wiley, J.), Sons Publishers, New York. pp. 1–13.

Green, S. (2009). *Measurements of Sap Flow by the Heat-Pulse Method. An Instruction Manual for the HPV system*. Palmerston North, New Zeland. 50pp.

Green, S., Clothier, B. and Jardine, B. (2003). Theory and practical application of heat-pulse to measure sap flow. *Agronomy Journal* 5: 1371 – 1379.

Green, S.,Clothier,B. and Deurer, M. (2007). Measuring and modeling stress response of grapevines to soil-water deficits. In:*Understanding and Modeling Water Stress Effects on Plant Growth Processes.* (Edited by Davidson, P.), The Horticulture and Food Research Institute of New Zealand Ltd., Marlborough District Council, New Zealand. pp. 357 – 385.

Hunter, J., Volschenk, C., Novello, V., Pisciotta, A., Booyse, M. and Fouche, G. (2014). Integrative effects of vine water relations and grape ripeness level of *Vitis vinifera* L. cv. 'Shiraz'/'Richtes II', grape composition and grape quality. *South African Journal of Enology Viticulture* 35(2): 359 – 374.

Hussein, S. (2010). Value chain analysis of grapes in Tanzania. Dissertation for Award of MSc Degree at Sokoine University of Agriculture. Morogoro, Tanzania, 124 pp.

Iland, P. G., Ewarts, A., Sitters, J., Markides, A. and Bruers, N. (2000). *Technologies for Chemical Analysis and Quality Monitoring During Wine Making.* Wine Promotions, Campbell Town, Australia. 99pp.

Keller, M., Smith, J. and Bondara, B. (2006). Ripening grape berry remain hydralically connected to the shoot. *Journal of Eperimental Botany* 57: 2577 – 2582.

Kose, B. (2014). Effect of light Intensity and temperature on growth and quality parameters of grafted vines. *Romanian Journal of Agricultural Sciences and Veterinary Medicene* 42(2): 507 – 515.

Koundouras, S., Kanakis, I., Drossou, E., Kallithraka, S. and Kotseridis, Y. (2013). Influence of post-veraison water status on the phenolic composition of grapes and wines of cv. Agiorgitiko (*Vitis vinifera* L.) grown in Nemea. *International Journal of Science of Vine and Wine* 47(1): 115 – 128.

Lamm, F. and Trooine, T. (2003). Subsurface drip irrigation for corn production: a review of 10 years ofresearch in Kansas. *Irrigation Science* 22: 195 – 200.

Leeuwen, C., Tregot, O., Chone, X., Bois, B., Pernet, D. and Gaudillere, J. (2009). Vine water status is a key factor in grape ripening and vintage quality for red bordeaux wine. how can it be assessed for vineyard management purposes? . *Journal of International* 43(3): 121 – 134.

Lopez, I., Ramirez, P. and and Morales, J. (2009). Influence of a deficit Irrigation Regime on the quality of wine made from white grapes grown in semi arid areas. *Journal of Food Quality* 32(4): 481 – 490.

Luscher, C., Kizildeniz, T., Vucetic, V., Dai, Z., Luedeling, E. and Leeuwen, C. (2016). Sensitivity of grapevine phenology to water availability, temperature and co2 concentration. *Frontier Environmental Science* 4: 1 – 48.

Lwelamira, J., Safari, J. and Wambura, P. (2015). Grapevine farming and its contribution to household income and welfare among mallholder farmers in Dodoma Urban District, Tanzania. *American Journal of Agriculture and Forestry* 3(3): 73 – 79.

Mahinda, A. (2014). Effect of drip irrigation on the production and economic returns of soghurm in semi arid areas of Tanzania. Dissertation for Award of MSc Degree at University of Nairobi.Nairobi, Kenya, 94pp.

Mahoo, H., Young, M. and Mzirai, B. (1999). Rainfall variability and its implications for the transferability of experimental results in the semi arid areas of Tanzania. *Tanzania Journal of Agricultural Science* 2: 127 – 140.

Mercker, D. F. (2011). *User Manual for Continuous Logging Probe.* Software Solution, Cape Town, South Africa. 20pp.

Mori, K. (2005). Decreased anthocyanin biosynthesis in grape berries grown under elevated night temperature condition. *American Journal of Horticultural Science* 105: 319 – 330.

Mrosso, L. (2007). Development of vineyard cultivation in Dodoma. *Proceedings of Central Zone Agricultural Research Steering Committee Meeting*. Dodoma, Tanzania, 23 May, 2007. 14pp.

Myburg, P. A. (2003). Responses of *Vitis vinifera* L. cv. 'Sultanina' to water deficits during various pre and post harvest phases under semi-arid conditions. *South African Journal of Enology and Viticulture* 24: 35 – 40.

Ozden, M., Vardin, H., Simsek, M. and Karaaslan, M. (2010). Effects of rootstocks and irrigation levels on grape quality of *Vitis vinifera* L. cv. 'Shiraz'. *African Journal of Biotechnology* 9(25): 3801 – 3807.

Payero, J. O., Tarkalson D. D., Irmak S., Davidson, D. and Petersen, J. L. (2008). Effect of irrigation amounts applied with subsurface drip irrigation on corn evapotranspiration, yield, Water productivity, and dry matter production in a semiarid climate. *Agricultural Water Management* 95: 895 – 908.

Pieri, P. and Gaudillere, J. (2005). Vines water stress derived from a soil water balance model – sensitivity to soil and training parameters. In: *Proceedings of the 15th International Conference*. (Edited by Shultz, H.), German Viticulture Congress, Geisenheim, Germany. pp. 457 – 463.

Roby, G. and Matthews, M. (2004). Relative proportions of seed, skin and flesh, in ripe berries from Cabernet Sauvignon grapevines grown in a vineyard either well irrigated or under water deficit. *Australian Journal of Grape Wine Research* 10: 74 – 82.

Romero, P., Fernández, J., Muñoz, R. and Botía, P. (2016). Vigour-yield-quality relationships in long-term deficit irrigated winegrapes grown under semiarid conditions. *Theoretical and Experimental plant Physiology* 28(1): 23 – 51.

Rwebugisa, R. (2008). Ground water recharge assessment in the Makutupora basin, Dodoma Tanzania. Thesis for the Award of Masters Degree at International Institute for Geo-Information Science and Earth Observation. Enschede, Netherlands, 111pp.

Santos, T., Lopes, C. L. and Souza, C. R. J. (2007). Effects of deficit irrigation strategies on cluster microclimate for improving fruit composition of Moscatel field-grown grapevines. *Science Horticulture* 112: 321 – 330.

Shikhamany, S. (2000). Grape production in India. In: *Corporate Documentary Repository-Grape Production in the Asia-Pacific Region.* (Edited by Papademetriou, M. K. and Dent, F. J.), Bangkok, Thailand. pp. 28 – 37.

Stern, R., Buysse, W. and Coe, R. (2004). *GenStat Discovery Edition for Everyday Use*. ICRAF Nairobi, Kenya. 114 pp.

Terry, D. and Kurtural, S. (2011). Achieving vine balance of Syrah with mechanical canopy management and regulated deficit irrigation. *American Journal of Enology Vitic* 62: 426 – 437.

Yang, J., Martinson, T. E. and and Liu, R. H. (2009). Phytochemestry profile and antioxidant activities of wine grapes . *Journal of Food Chemistry* 116: 332 – 339.

Zarrouk, O., Francisco, R., Pinto, M., Brossa, R., Santos, R. and Pinheiro, C. (2012). Impact of irrigation regime on berry development and flavonoids composition in Aragonez (cv. 'Tempranillo') grapevine. *Agricultural Water Management* 114: 18 – 29.

Zerizghy, G. and Rensburg, L. (2013). Comparison of neutron scattering and capacitance instruments in measuring soil water evaporation. *Water South Africa* 39(2): 25 – 38.

CHAPTER FOUR

4.0 DOES DEFICIT IRRIGATION INCREASE WATER PRODUCTIVITY AND IMPROVE GRAPE QUALITY OF cv. 'Makutopora red'?

Abstract

In Dodoma water is scarce and irrigation management emphasizes on maximizing water productivity. The use of deficit irrigation can reduce irrigation water use and improve grape quality. Grapevines interpretation of responses to drought differs depending on the parameter chosen to express Water productivity (WP).In this study Water productivity by yield and Water productivity by quality were used to investigate the relation between the grape yield and quality and the amount of water used by grapes cv. 'Makutupora red'. Irrigation regimes were formed by interacting irrigation levels which were100% of crop evapotranspiration (ET_c), 63.5% of ETc, 56.3% of ETc and 48.9% of ET_c and irrigation methods that were conventional deficit irrigation (CDI), partial root zone drying (PRD) and root zone deficit rationing (RDR). The response of vines under different irrigation regimes on grape yield and quality were investigated. The use of drip deficit irrigation from fruit set to fruit maturity increased water productivity and improved quality of grapes in irrigation regimes (treatments) CDI at 63.5% and 56.3 of ET_c and in RDR at 63.5% which produced optimum yields with good grape quality and had high Water productivity. In all full irrigated regimes (at 100% of ET_c) vines produced gave higher grape yields with low grape quality which caused lower Water productivity. Total soluble solids, alcohol, phenols and anthocyanins were higher in deficit irrigated grapes than in full irrigated vines. Malic acid and tartaric acid did not show significant difference between full irrigated grapes and grapes subjected to deficit irrigation. The relationship between water use, grape yield and quality showed that Moderate deficit irrigation

improved Water productivity while full irrigation and severe deficits showed no improvement.

Key words: Deficit irrigation, Water productivity, grape yield and grape quality

4.1 Introduction

Grapevine irrigation is an important practice to guarantee plant survival and grape quality in areas affected by drought (Espinoza *et al.*, 2015). In areas where water is abundant its use may not be very crucial when looking at economic implications. However, minimizing the use of water in drought areas is very important especially when availability of water tends to be more important than the cost of water. Some vineyards under irrigation in Dodoma have been abandoned due to the low income generated that did not justify the cost of water consumption, public water supply limitations, competition with domestic water requirement, unstable grape and wine market and water inadequacy for application in vineyards due to scarcity and inefficient application of water. Currently, the application of drip irrigation has improved the efficiency of using irrigation water. The use of deficit irrigation will further minimize the use of water for vineyard irrigation, improve grape quality, strengthen grape and wine market environment (Chaves *et al.*, 2007). In Dodoma information on deficit irrigation in vineyards is inadequate, only the technique of cutting off irrigation water application 15 to 30 days before grape harvest has been used to improve grape quality but yet the quality of grapes has been observed to be low (Mrosso, 2007). Investigation on using water rates that will give high water productivity while improving grape quality is highly required. Most of grapevines grown in Dodoma about 90% are cv. ‘Makutupora red’ which is a drought tolerant cultivar. It is highly productive and long maturing. Dodoma being in the subtropics, growers harvest grapes twice per annum with one harvest during the rainy season (February- March) and another one during the dry season (August-September) (Mrosso, 2007; Hussein, 2010).

It is common to have two harvests per year for vineyards in subtropical climates or near the equator (Jones, 2012; Camargo *et al*., 2012; Seccia *et al.*, 2015).

In Dodoma grapes harvested in the rainy season are not used for wine making due to their low quality as a result of high humidity, diseases, high temperatures and rains (December – April) (Hussein, 2010). Grapes harvested in the dry season have high quality but the grape yield is low. It has been observed that with irrigation, grape yield can be increased (Mrosso, 2007). However, despite the increase in yield, there has been a decrease in grape quality (CETAWICO, 2010). The cause of low quality is probably due to excessive application of water at fruit set to beginning of fruit ripening when grapevines require less water (Rodriguez *et al*., 2007; Chaves *et al*., 2007; Espinoza *et al*., 2015). If water applied is reduced, grape quality can be maintained or even improved (Conceicao *et al.,* 2013; Genebra *et al.,* 2014). The amount of water to be applied for cv. 'Makutupora red' grown in Dodoma must be carefully determined in order to maintain high yield and good quality of grapes.

A number of studies have been conducted to determine the optimal quality and yield of grapes through systematic regulation of amount of water supplied to the vines (Casassa *et al.,* 2015; Castellarin *et al.,* 2015). Mostly, conventional deficit irrigation (CDI) and partial root zone drying (PRD) have been used in regulating irrigation regimes that is the amount of water applied and the pattern of water application to the plant (Teixeira *et al.,* 2007; Chaves *et al.,* 2010; Koundouras *et al.,* 2013).Green *et al.* (2007) found that grape quality and yield were optimal when using irrigation level at 30% of ET_c (crop potential evapotranspiration) on cv. 'Sauvignon blanc'. Ozden *et al.,* 2010 used irrigation level between 50% and 25% of ET_c and found that irrigation level below 25% lowers the yield and quality of grapes on cv. 'Shiraz'. Stressing plants by controlling water application for

manipulating vegetative growth and berry composition has shown to produce inconsistence outcomes among grapevine cultivars (Chaves *et al*., 2010, Costa and Rodrigues, 2012, Medrano *et al.*, 2015; Zarrouk *et al.*, 2012).

It is therefore, important to investigate individual grape cultivars in order to understand to what extent grape yields and quality are affected by different levels of water deficits (Chaves *et al.*, 2010; Costa and Rodrigues, 2012; Kuhn *et al.*, 2014; Tomas *et al.*, 2014). The aim of this study was to find a relationship between irrigation regimes, grape yield and quality of cv. 'Makutopora red' that will assist to understand its response to different irrigation regimes for selecting options that will produce optimum grape yield and quality with effective use of irrigation water.

4.2 Materials and Methods

4.2.1 Description of the study area and the plant material

The study was carried out in Dodoma at Makutupora Agricultural Research Institute (ARI-Makutupora) which is located at latitude $5^0 58' 669''$ S and longitude $35^0 46' 093''$ E about 26 km North of Dodoma Municipality. The area lies at an altitude of 1050m above sea level (Mahinda, 2014). The annual rainfall at ARI Makutupora ranges from 530 mm to 660 mm (Hussein, 2010) and are mostly received in the months of December, January, February and March. May to October is a dry season (Mahoo *et al.*, 1999). The average annual air humidity is 65%, Average minimum daily temperature is 15 °C and average maximum temperature is 32 ^{O}C and sunshine hours are almost 12 per day, wind speed ranges between 1.0 m/s in February to 4 m/s in October (Hussein, 2010).

4.2.2 Crop management

The plant material was *Vitis* vinifera L. cv. 'Makutupora red' planted in 2004 on 0.4 ha at ARI-Makutupora with spacing of 1.5 m within a row and 2.5 between rows. The rows are in East-West orientation with the sun overhead at noon. Part of the vine yard of 0.2 ha was subdivided into sub-plots. The number of plants in each sub-plot was 9 (7.5 m x 4.5 m). During the trial the vines were thoroughly managed with timely weed control, pruning, pest control, de-suckering, manure addition and vermin control such that the vines did not succumb to any stress. Pruning was extended cordon trellis with short spur. Farmyard manure was added in the soil at 20 Mg/ha in February (2014) and chemical inputs (ridomil 6 g/l, anvil 0.5 ml/l and sumithion 1 ml/l) were timely sprayed for the control of powdery mildew, dawn mildew and pests respectively (Hussein, 2010).

4.2.3 Water use determination

Water used for transpiration per mature plant of cv. 'Makutupora red' vines grown for wine production without stress during two growing seasons (2014–2015) was measured. Vines were irrigated using drip irrigation system. Compensation heat pulse method (6 x 2 channels) was used to determine vines daily water consumption per plant from pruning to fruit maturity as explained by (Green, 2009; Suvocarev *et al.*, 2013). Instruments used were a set of sap flow sensors with CR 1000 data logger. Water lost through evaporation per plant was also determined on daily basis by using soil moisture probes as explained by Allen *et al.* (1999), the user guideline for continuous logging probes Mercker (2011) and Zerizghy and Rensburg (2013).

The daily water use was determined from readings taken from the full irrigated vines and was used for getting daily water application for irrigation levels V1, V2, V3 and V4. The mean daily water applications are shown in Table 4.1. Mean daily evapotranspiration

(ET_c) was 4.31 mm in 2015 and 3.28 mm in 2014. V1, V2, v3 and V4 were computed as fractions of ET_c. Total seasonal water applications to the vines are shown in Table 4.1.

Table 4.1: Total amount of water applied in a season for each irrigation level (mm)

		IL	AWPD	Days	TWAPS
Season 1 (2014)					
	1	V1	4.31	135	582.26
	2	V2	2.69	135	368.11
	3	V3	2.37	135	319.30
	4	V4	2.03	135	274.70
Season 2 (2015)					
	1	V1	4.28	135	577.57
	2	V2	2.77	135	373.30
	3	V3	2.47	135	333.39
	4	V4	2.17	135	292.30

Where, V1 = ET_b + ET_e= 100% of ET_c
V2 = 0.5*ET_b + ET_e = 63.5% of ET_c
V3 = 0.4*ET_b + ET_e = 56.3% of ET_c
V4 = 0.3*ET_b + ET_e = 48.9% of ET_c
ET_e = Daily evaporation (mm/*day*) = Amount of water that is lost through evaporation per day (mm/day)
ET_b = Daily transpiration (mm/*day*) = Amount of water that is consumed by the vines per day (mm/day)
ET_c= Crop evapotranspiration = ET_b + ET_e = Plant water requirement per day (mm/day)
IL = Irrigation level
AWPD = Applied water in mm/day (mean seasonal amount of irrigation water applied per day)
TWAPS = AWPD * 135 = Total amount of water applied in a season (mm/season)

4.2.4 Experimental design

The experiment was a split plot design with four replications (Appendix 3). The main factor was irrigation levels obtained by adding evaporation to the fractions of transpiration (ET_b) which were V1 (ET_e + 100% of ET_b), V2 (ET_e + 50% of ET_b), V3 (ET_e + 40% of ET_b) and V4 (ET_e + 30% of ET_b). Potential transpiration (ET_b) and water lost through evaporation (ET_e) were determined by the compensation heat pulse method as explained by Green (2009) and evaporation as water lost to the atmosphere from the top layer of the soil was predetermined by method explained by Mercker (2011). Drip irrigation at 100% of crop water requirement was the reference. The water rationing was applied starting at fruit set to fruit maturity. The sub factor was drip irrigation methods M1, M2 and M3 (conventional deficit irrigation-CDI, root zone deficit rationing-RDR

and partial root zone drying-PRD). Grapes in the experiment plots were harvested for analysis on 22th of September in 2014 (season 1) and 28th of August in 2015 (season 2) 175 days from the day of pruning for plots under deficit irrigation (pruning dates were 8th of May in 2014 and 15th of April in 2015).

4.2.5 Water productivity

Water productivity (WP) was determined by calculating the ratio of the mass of harvested grapes per vine to the total amount of water applied to the vine in a season (Mahinda, 2014) (Equation 12).

$$\boldsymbol{WP} = \frac{\boldsymbol{yield}}{\boldsymbol{TAW}} \quad \ldots\ldots (12)$$

Where: *WP* = Water productivity *g/l*

Yield = Grape yield per vine in kg

TAW = Total amount of water applied to a plant in a season (mm)

Water productivity by quality (WPQ) was determined by calculating the ratio of the mass of total soluble solids to the total amount of water applied to the vine in a season (Equation 13).

$$\boldsymbol{WPQ} = \boldsymbol{a} * \boldsymbol{Tss} * \frac{\boldsymbol{Yield} * \boldsymbol{\rho_g}}{\boldsymbol{TAW} * \mathbf{100}} \quad \ldots\ldots (13)$$

Where: *WPQ* = Water productivity by quality in *g/l*

a = Factor based on the volume of grape juice from a unit mass of grapes which ranges between 0.5 and 0.7. For converting one kilogram of 'Makutupora red' to an equivalent volume in liters (*l/kg*) *a* = 0.6.

ρ_g= Density of grape juice in *kg/l*

TSS= Total soluble solids in °Brix

Yield= Grape yield per vine in kg

TAW= Total amount of water applied to a plant in a season *(l*)

Note: °Brix is in percentage and is divided by 100 to obtain a fraction of total soluble solids from the grape juice.

The Water productivity by quality gives the mass of total soluble solids per plant per unit volume of water applied in a season and is an appropriate gauge of grape quality status with respect to the amount of water used by the vines.

4.3 Data Analysis

Vines water consumption, quality and yield components data were collected and subjected to multiple regressions to get their correlation coefficients using GENSTAT 13, 2011 based on a split-plot design. The data were also used to calculate water productivity (WP) and water productivity by quality (WPQ) for each treatment in the two seasons and were subjected to analysis of variance (ANOVA), the test of significant differences of their mean values across treatments were performed based on Duncan multiple range test at a probability value of 0.05 ($P \leq 0.5$) for selecting treatments that produced optimum yield, good quality grapes with effective use of irrigation water.

4.4 Results and Discussions

4.4.1 Water productivity (WP)

The results showed that water productivity was improved with moderate deficits at 63.5% of ET_c (V2) and was low both in full irrigation regimes at 100% of ET_c (V1) and in increased deficit irrigation regimes at 48.9% of ET_c (V4)as shown in Table 4.2. Phogat *et al.* (2015) found that water productivity was improved by application of moderate deficit drip irrigation on *Vitis vinifera* L. cv. 'Chardonnay' on Ramsey rootstock at Waikerie in South Australia.

Table 4.2: Effect of water levels on water productivity

Level	Yield (kg/vine)	TSS (ºBrix)	WP* (g/l)
V1	6.40d	20a	**9.58a**
V2	4.92c	23b	**11.32b**
V3	3.77b	25c	10.03a
V4	3.22a	27d	**9.83a**
S.e.d	0.22	0.3	0.52
L.s.d	0.49	0.8	1.18

*Means of 24 readings of WP across irrigation levels; In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means; L.s.d = Least significant differences of means, Gm = Grand mean, and V1=100% of transpiration + evaporation, V2=50% of transpiration+ evaporation, V3= 40% of transpiration + evaporation V4=30% of transpiration + evaporation.

CDI method showed significantly higher Water productivity than RDR and PRD meaning that at the same irrigation level grape yields were significantly lower in RDR and PRD treatments than in CDI treatments. Water productivity was lowest in PRD (M3) (Table 4.3).Chaves *et al.* (2010) found that water productivity was higher in conventional drip irrigation than in partial root zone drying.

Table 4.3: Effect of irrigation methods on water productivity

Method	Yield (Kg/vine)	TSS (ºBrix)	WP* (g/*l*)
M1	5.04b	23a	**11.38c**
M2	4.17a	25c	**9.16a**
M3	4.51a	24b	10.06b
S.e.d	0.18	0.1	0.44
L.s.d	0.40	0.3	0.91

*Means of 32 readings of WP across irrigation methods; In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means; L.s.d = Least significant differences of means, Gm = Grand mean, M1 = Conventional deficit irrigation CDI, M2 = Partial root zone drying PRD and M3 = Root zone deficit rationing RDR.

Water productivity was improved in irrigation regimes with convention deficit irrigation (CDI) at moderate water levels (63.5% and 56% of ET_c) and root zone deficit rationing (RDR) at 63.5% of ET_c and was higher in irrigation regimes V2M1, V2M3 and V3M1 (Table 4.4).

V2M1 treatments had optimum grape yield per plant. The water applied was 63.5% of full irrigated vines (V2) which resulted into the highest water productivity. In these treatments the vines were evenly and moderately stressed in the root zone. The stress was mild without causing much decrease in grape yield.V3M1 produced high water productivity although its grapes were more water stressed it still produced a good grape yield at 56.3% of ET_c.V2M3 treatment also produced high water productivity with water application at 63.5% of ET_c. In this treatment, the vines were rationally stressed in which case one side received two thirds of water applied and the other side received the remaining one third. The rationing of water application was alternated after every fourteen days between sides of the vine's root zone such that roots damage was minimized. These results are similar to Williams *et al*. (2010) who found that optimum grape yields and quality were achieved when applying water at 60–80 % of ET_c.

Table 4.4: Interaction effect irrigation regimes on water productivity

Irrigation regime	Yield (Kg/vine)	WP* (g/*l*)
V1M1	6.84e	10.24cba
V2M1	5.39d	**12.74e**
V3M1	4.49b	**11.98ed**
V4M1	3.45a	10.54dcb
V1M2	5.79d	8.68a
V2M2	4.50cb	9.78cba
V3M2	3.35a	8.92a
V4M2	3.02a	9.24ba
V1M3	6.55e	9.82cba
V2M3	4.86dcb	**11.46edc**
V3M3	3.45a	9.18ba
V4M3	3.19a	9.77cb
Gm	**4.57**	**10.2**
S.e.d	0.36	0.89
L.s.d	0.74	1.61
F-test	0.541	0.447
CV%	10.9	12.3

*Means of 8 readings of WP across irrigation regimes; In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means; L.s.d = Least significant differences of means, Gm = Grand mean, and V1 = 100% transpiration + evaporation, V2 = 50% of transpiration + evaporation, V3 = 40% of transpiration + evaporation V4 = 30% of transpiration + evaporation , M1 = Conventional deficit irrigation CDI , M2 = Partial root zone drying PRD and M3 = Root zone deficit rationing RDR.

4.4.2 Water productivity by quality (WPQ)

Water productivity shows effective use of water in relation to grape yield but do not give sufficient information on the status of the grape quality (Chaves *et al.*, 2010). Water productivity by quality (WPQ) was used to assess the effect of amount of water supplied to both grape yield and grape quality. Results showed that full irrigation treatments (regimes) had low WPQ and irrigation regimes with water deficit had high WPQ and there was no significant difference in WPQ among treatments with deficit irrigation (Table 4.5).

Water productivity by quality was low in full irrigated regimes but high in all irrigation regimes with water deficits. It was observed that increasing water deficits did not change the water productivity by quality because the mass of soluble solids was increased by water deficit at moderate range and further increase of water deficit beyond moderate range was just reducing the berry volume and increasing TSS concentration but the total mass of TSS in the berry remained constant (Table 4.5). Conceicao *et al.* (2013) found that excessive deficit irrigation at veraison increased concentration by shrinkage of the berries whereas the overall berry composition was not significantly altered.

Table 4.5: Effect of irrigation levels on water productivity by quality

Level	Yield (Kg/vine)	TSS (ºBrix)	WPQ* (g/l)
V1	6.40a	20a	1.13a
V2	4.92b	23b	**1.58b**
V3	3.77c	25c	**1.48b**
V4	3.22d	27d	**1.59b**
S.e.d	0.22	0.3	0.08
L.s.d	0.49	0.8	0.17

*Means of 24 readings of WPQ across irrigation levels; In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means; L.s.d = Least significant differences of means, Gm = Grand mean, and V1=100% of transpiration + evaporation, V2 = 50% of transpiration+ evaporation, V3= 40% of transpiration + evaporation V4=30% of transpiration + evaporation**.**

Convention drip irrigation (CDI) showed relatively higher WPQ than in partial root zone drying (PRD) whereas root zone rationing (RDR) produced water productivity by quality which was moderate and did not differ significantly from WPQ of CDI and PRD (Table 4.6).

Table 4.6: Effect of irrigation methods on water productivity by quality

Method	Yield (Kg/vine)	TSS (ºBrix)	WPQ* g/l
M1	5.04b	23a	1.54b
M2	4.17a	25c	**1.36a**
M3	4.51a	24b	1.43ba
S.e.d	0.18	0.1	0.07
L.s.d	0.40	0.3	0.14

*Means of 32 readings of WPQ across irrigation methods; In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means; L.s.d = Least significant differences of means, Gm = Grand mean, M1= Conventional deficit irrigation CDI, M2=Partial root zone drying PRD and M3= Root zone deficit rationing RDR.

Treatments V1M1, V1M2 and V1M3 had low WPQ whereas V2M1, V2M3 and V3M1 recorded highest WPQ with no significant difference with other treatments with deficit irrigation which were V2M2, V3M2, V3M3, V4M1, V4M2 and V4M3 (Table 4.7). The results showed that yield was significantly higher in regimes at full irrigation levels (V1M1, V1M2 and V1M3 treatments) but WPQ was significantly lower where as in all regimes with deficit irrigation the yield decreased but WPQ was significantly improved.

Table 4.7: Interaction effect of irrigation regimes on water productivity by quality

Irrigation Regime	Yield (Kg/vine)	TSS (ºBrix)	WPQ* (g/*l*)
V1M1	6.84e	19a	1.15ba
V2M1	5.39d	22c	**1.72d**
V3M1	4.49b	24e	**1.72d**
V4M1	3.45a	25f	1.59dc
V1M2	5.79d	20b	**1.05a**
V2M2	4.50bc	24e	1.41cb
V3M2	3.35a	26g	1.38cb
V4M2	3.02a	29i	1.61dc
V1M3	6.55e	20b	**1.18ba**
V2M3	4.86dcb	23d	**1.61dc**
V3M3	3.45a	24e	1.35cb
V4M3	3.19a	27h	1.58dc
Gm	**4.57**	**23.6**	**1.45**
S.e.d	0.36	0.4	0.14
L.s.d	0.74	0.8	0.28
F-test	0.541	0.001	0.301
CV%	10.90	1.5	13.60

*Means of 8 readings of WPQ across irrigation regimes; In each column, statistically significant differences between means of yield components are indicated by different letters based on Duncan multiple range test at a probability value of ≤ 5% (P≤0.05), S.e.d = Standard error of differences of means; L.s.d = Least significant differences of means, Gm = Grand mean,V1 = 100% of transpiration + evaporation, V2 = 50% of transpiration + evaporation, V3 = 40% of transpiration + evaporation V4 = 30% of transpiration + evaporation , M1= Conventional deficit irrigation CDI , M2 = Partial root zone drying PRD and M3 = Root zone deficit rationing RDR.

The results showed that treatments V2M1, V3M1 and V2M3 produced high water productivity than other treatments with deficit irrigation although there is no significant difference. V2MI, V3M1 and V2M3 also produced effective water use (had higher WP) and showed to be good options for producing optimum grape yield and good quality under deficit drip irrigation.

4.4.3 Correlations among yield and quality components

The correlations of grape yield and quality components are shown in Table 4.8 (Appendix 2).

Table 4.8: Correlation among yield and quality components

yield	1.000															
LAI	0.599															
Pm	0.688	**0.847**														
Bd	0.771	0.617	0.668													
Bw	0.740	0.638	0.643	**0.803**												
Cw	**0.988**	0.590	0.680	0.759	0.756											
CN	0.600	0.439	0.454	0.520	0.435	0.593										
TSS	**-0.871**	-0.531	-0.640	-0.716	-0.692	-0.861	-0.6159									
Alco	**-0.871**	-0.517	-0.634	-0.706	-0.703	-0.867	-0.6009	**0.988**								
TTA	0.433	0.240	0.143	0.310	0.299	0.442	0.3265	-0.434	-0.466							
T/T	-0.823	-0.496	-0.530	-0.673	-0.647	-0.821	-0.6042	**0.918**	0.924	-0.747						
pH	0.515	0.217	0.435	0.493	0.463	0.528	0.1319	-0.509	-0.528	0.059	-0.396					
Phenol	**-0.899**	-0.534	-0.680	-0.725	-0.713	-0.891	-0.5928	**0.980**	0.988	-0.437	0.906	-0.587				
anth	**-0.892**	-0.528	-0.689	-0.732	-0.715	-0.887	-0.5783	**0.971**	0.978	-0.41	0.888	-0.618	0.997			
Tar	-0.036	-0.036	-0.032	-0.133	-0.095	-0.035	-0.1547	0.003	-0.023	0.504	-0.184	-0.165	-0.002	0.007		
Mal	0.300	0.247	0.355	0.230	0.302	0.329	0.2326	-0.442	-0.465	0.216	-0.397	0.269	-0.444	-0.451	0.527	1.000
	yield	**LAI**	**Pm**	**Bd**	**Bw**	**Cw**	**CN**	**TSS**	**Alco**	**TTA**	**T/T**	**pH**	**Phenol**	**anth**	**Tar**	**Mal**

Where yield = grape yield kg/vine, LAI = Leaf area index m^2/m^2, Pm = Pruned mass g/vine, Cw = cluster weight g, Bd = berry diameter mm, Bw = berry weight g, TSS = grape juice total soluble solids %, TTA = Total titratable acids g/*l*, T/T = The ratio of total soluble solids to the total titratable acids, Alco = alcohol p of wine after fermentation of grape juice %, Phenol = phenol concentration in the grape juice g/l, Anth = concentration of anthocyanins in the grape juice in mg/*l*, Tar = Tartaric acid g/*l*, Ma = Malic acidg/*l*, WP = Water productivity g/*l*, WPQ = Water productivity by quality g/*l*.

There were positive correlations between yields per plant with pruned mass, leaf area index, fruit weight, and fruit diameter, cluster number per tree and bunch weight. Grape yield per plant was closely correlated to bunch weight with coefficient of correlation (r) of 0.97. Yield showed negative correlation with total soluble solids, wine alcohol percentage, phenols and anthocyanins. Total soluble solids (TSS) had positive correlations with wine alcohol percentage, phenols and anthocyanins and had no remarkable correlations with fruit juice pH, total titratable acids, malic acid and tartaric acid. Total soluble solids had negative correlations with grape yield per plant, pruned mass, fruit weight, fruit diameter, bunch weight and cluster number per tree. Total soluble solids closely correlated to the ratio of total soluble solids to total titratable acids with correlation coefficient of 0.918. The contents in total soluble solids (TSS) are the most important traits influencing berry quality.

4.4.4 Relationship between crop water use, grape yield and quality

i. Relationship between grape yield and crop water use

Grape yield showed a linear relation with vine water use between 4.31 mm/day and 2.03 mm/day. The fitted values of grape yields are shown in Table 4.9. There was a positive correlation such that within that range of water consumption (2.03 – 4.31mm/day), grape yield increased with an increase in irrigation water application (Fig. 4.1). This relationship will not hold if the irrigation water exceeds 4.31 mm/day because the excess water will not increase grape yield. Grape yield will remain rather constant and if more water is applied, grape yield will drop due to over application of water that will cause other problems like poor root aeration and diseases (Chaves *et al.*, 2007). Whereas, if irrigation water is over reduced, the vines will be damaged and fail to bear fruits. Equation 14 shows when application of irrigation water is zero, the vines will produce 0.49 kg/vine which might not be the case because the vines will be overstressed by water

deficit and can be permanently damaged. Ozden *et al*. (2010) observed that even in PRD, alternating irrigated and dry sides should be done within a period of 14 days otherwise the roots in the side that is not receiving water get damaged.

Table 4.9: Relationship between grape yield and crop water use

	ET_c (mm/d)	Yield (kg/vine)	Yield Fitted values (kg/vine)
	2.03	3.03	3.34
	2.17	3.41	3.54
	2.37	3.52	3.82
	2.47	4.01	3.96
	2.69	4.55	4.27
	2.77	5.05	4.38
	4.28	6.21	6.50
	4.31	6.58	6.55
Correlation Coefficient (r^2)			**92.1**
Standard error of observation			**0.369**
Regression coefficient			**1.41**
A constant			**0.49**

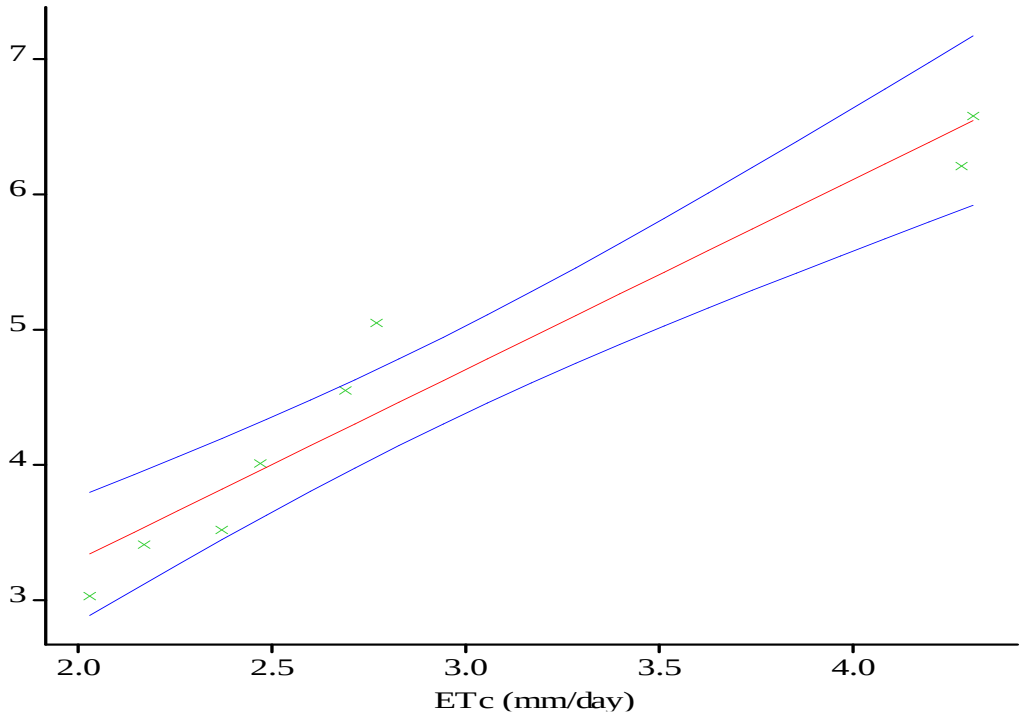

Figure 4.1: Fitted and observed yield values versus ETc with 95% confidence limits.

$$\boldsymbol{Yield}\ \left(\frac{\boldsymbol{kg}}{\boldsymbol{vine}}\right) = \boldsymbol{a_1} * \boldsymbol{ET_c} + \boldsymbol{b_1} \quad \text{(14)}$$

Where, Yield =Weight of grapes harvested per vine kg/vine

a_1 = a constant = 1.41 kg day/mm/vine

ET_c= Crop water use (mm/day)

b_1= A constant kg/vine

ii. Relationship between grape yield and crop water use

Grape quality showed a negative linear relationship with crop water use between 4.31 mm/day and 2.03 mm/day (Equation 15). The fitted values of TSS are shown in Table 4.10. There was a negative correlation such that within that range of water consumption (2.03 – 4.31 mm/day), TSS decreased with an increase in irrigation water application (Figure 4.2). This relationship will not hold if the irrigation water drops below 2.03 mm/day, because grape quality will decrease due to excessive water stress that will hinder nutrients uptake of the vines. if more water is applied, grape quality will drop to what they call bad quality due to over application of water that will cause other problems like unwanted berry fungal diseases which cannot be controlled if humidity around the vines is high (Chalmers, 2010).

Table 4.10: Relationship between TSS and crop water use

	ET_c (mm/d)	TSS (°Brix)	TSS Fitted values (°Brix)
	2.03	27	26.33
	2.17	27	25.88
	2.37	25	25.25
	2.47	25	24.94
	2.69	23	24.24
	2.77	23	23.99
	4.28	19	19.23
	4.31	20	19.14
Correlation coefficient (r^2)			**90.4**
Standard error of observation			**0.922**
Regression Coefficient			**-3.15**
A constant			**32.73**

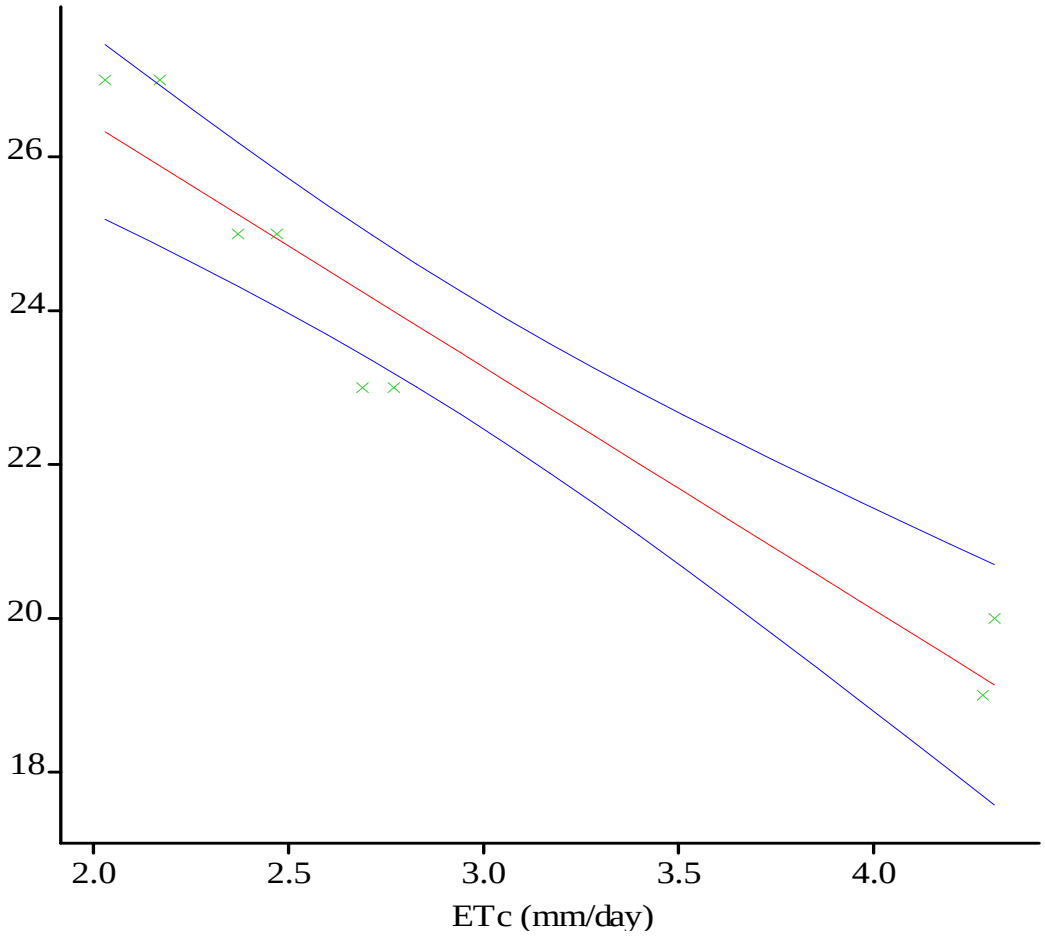

Figure 4.2: Fitted and observed TSS values versus crop water use with 95% confidence limits.

$$TSS\ (°Brix) = a_2 * ET_c + b_2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (15)$$

Where, TSS = Total soluble solids in °Brix

a_2 = a constant = -3.15 °Brix day/mm

ET_c= Crop water use (mm/day)

b_2= A constant °Brix

iii. Relationship between grape yield and crop water use

Relationship between TSS and grape yield/vine is shown in Table 4.11. Grape quality and grape yield are inversely related such that if grape yield/vine is increased, grape quality is decreased (Figure 17). Ozden *et al.* (2010), Green *et al.* (2003), Chaves *et al.* (2007) and Phagot *et al.* (2016) found that, in red grapes, an increase in yield per vine at full irrigation is accompanied by a decrease in quality whereas a decrease in yield/vine due to deficit irrigation is accompanied by improvement in grape quality. Equation 16 gives a linear relationship between grape yield/vine and grape quality. Regression coefficient is -2.19 and the constant is 33.58, meaning that with decreasing yield, the grape quality is improved within a certain range of TSS between 18 and 30 °Brix. Because below 18 °Brix, the grapes become too acidic and above 30 °Brix, grape yield is approaching zero and quality cannot be defined in absence of the produce (grapes). With these three equations, one can predict the quality or yield of grapes if the amount of water to be applied is known.

Table 4.11: Relationship between TSS and grape yield/vine

	Yield (kg/vine)	TSS (°Brix)	TSS Fitted values (°Brix)
	3.03	27	26.94
	3.41	27	26.11
	3.52	25	25.87
	4.01	25	24.80
	4.55	23	23.61
	5.05	23	22.52
	6.21	19	19.98
	6.58	20	19.17
Correlation coefficient (r^2)			**0.92**
Standard error of observation			**0.801**
Regression Coefficient			**-2.19**
Constant			**33.58**

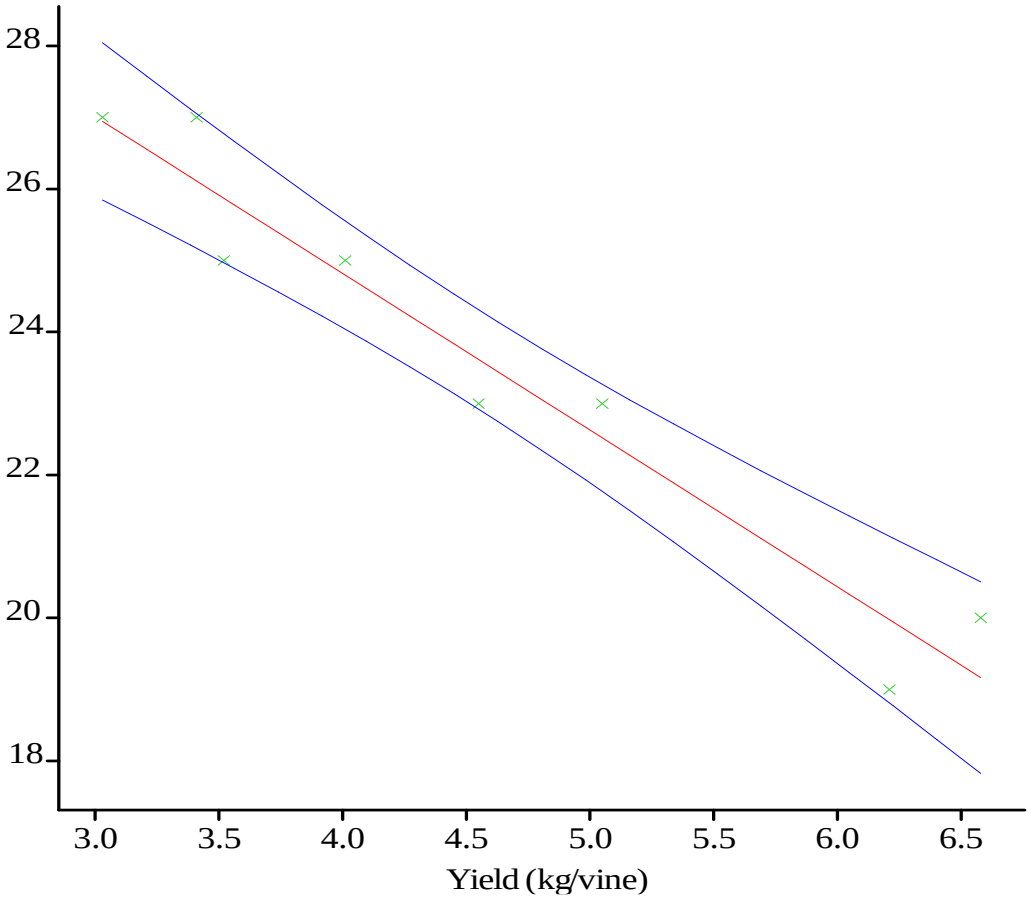

Figure 4.2: Fitted and observed TSS values versus grape yield with 95% confidence limits.

$$\boldsymbol{TSS\ (Brix) = a_3 * Yield + b_3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{16})$$

Where, TSS = Total soluble solids in °Brix

a_3 = a constant = -3.15 °Brix kg/vine

Yield=Weight of grapes harvested per vine kg/vine

b_3= A constant °Brix

4.5 Conclusion

Moderate deficit irrigation showed improvement in grape yield per unit of water applied. This is to say water productivity was higher at 63.5% of ET_c (V2) than in other irrigation levels. At full irrigation (100% of ET_c) water productivity was low and increasing irrigation deficit to less than 56.3% of ET_c produced a decrease in water productivity. Moderate deficit irrigation improved water productivity while severe deficits showed no improvement.

Deficit irrigation improved Water productivity by quality (WPQ) which increased with the increase of water stress to the vines. There was an improvement in WPQ even at 48.9 % of full irrigation water (V4). There was no significant difference among water stressed treatments meaning that stressing the vines beyond 63.5% of evapotranspiration did not increase the amount of substances comprising total soluble solids in a berry but it increased the concentration.

Deficit irrigation improves grape quality but decreases grape yield. Grape yield was positively correlated to fruit weight, cluster weight, pruned mass and leaf area index that were vegetative components that were decreasing with a decrease in the amount of irrigation water supplied to the vines whereas, grape juice total soluble solids was

positively correlated to juice phenols and anthocyanins concentrations and alcohol percent were increasing with a decrease in the amount of irrigation applied to the vines.

4.6 Recommendations

Application of deficit irrigation is recommended for grape cv.' Makutupora red 'for improving grape quality and efficient use of irrigation water. For achieving optimum grape yield and high quality, the application of deficit drip irrigation for cv. 'Makutupora red' at 63.5% of crop evapotranspiration (ET_c) is recommended for conventional deficit irrigation (CDI) and root zone deficit rationing (RDR) methods (V2M1 and V2M3 Treatments) and at 56.3% of evapotranspiration (ET_c) is recommended for CDI method (V3M1 treatment). The study was limited to application of irrigation water between 48.9 and 100% of crop evapotranspiration (ETc), further investigation on the response of vines to severe deficit to less than 48.9% of ETc and to over application beyond 100% of ETc, is recommended. For efficient use of irrigation water for grapevines further investigation on the application of deficit irrigation on other wine grape cultivars grown in Dodoma is recommended (e.g. *Vitis vinifera* L. cv. 'Makutupora white').

4.7 References

Camargo, U., Mandelli, F., Conceicao, M. and Tonietto, J. (2012). Grapevine performance and production strategies in tropical climates. *Asian Journal of Food Agro-Industry* 5(04): 257–269.

Casassa, F., Keller, M. and Harbertson, J. (2015). Regulated deficit irrigation alters anthocyanins, tannins and sensory properties of cabernet sauvignon grapes and wines. *Molecules* 20: 7820 – 7844.

Castellarin, S., Gambetta, G., Wada, H., Krasnow, M., Grant R. Cramer, G. and Peterlunger, E. (2015). Characterization of major ripening events during softening ingrape: turgor, sugar accumulation, abscisic acid metabolism,colour development, and their relationship with growth. *Journal of Experimental Botany* 67: 709 – 722.

Chaves, M., Zarrouk, O., Francisco, R., Costa, J., Santos, T. and Regalado, A. P. (2010). Grapevine under deficit irrigation: hints from physiological and molecular data. *Annals of Botany* 105: 661 – 676.

Chaves, M., Santos, T., Souza, C., Ortun, M., Rodrigues, M. and Lopez, C. (2007). Deficit irrigation in grapevine improves water-use efficiency while controlling vigour and production quality. *Annals of Applied Biology* 150: 235 – 252 .

Conceicao, M., Zepli, J. and Paula, M. (2013). Irrigation cutoff on 'BRS Clara' seedless grapevines during berry ripening stage. *Journal of Viticulture and Enology* 28(2): 167 – 170.

Costa,C. and Rodrigues, M. (2012). Deficit irrigation in Mediterranean vineyards - a tool to increase Water productivity and to control grapevine and berry growth. *Journal for International Society for Horticultural Sciences* **38(**10): 1421 – 1434.

Espinoza, C., Aspillaga, C., Ferreyra, R. and Selles, G. (2015). Response of table grape to irrigation water in the Aconcagua Valley, Chile. *Agronomy* 5: 405 – 417.

Genebra, T., Santos, R. and Serra, A. (2014). Proanthocyanidin accumulation and biosynthesis are modulated by the irrigation regime in tempranillo seeds.*International Journal of Molecolor Science* 15: 11862 – 11867.

Green, S. (2009). *Measurements of Sap Flow by the Heat-Pulse Method. An Instruction Manual for the HPV system*. Palmerston North, New Zeland. 50pp.

Green, S., Clothier,B. and Deurer, M. (2007). Measuring and modeling stress response of grapevines to soil-water deficits. In:*Understanding and Modeling Water Stress Effects on Plant Growth Processes.* (Edited by Davidson,P.), The Horticulture and Food Research Institute of New Zealand Ltd., New Zealand. pp. 357 – 385.

Green, S., Clothier, B. and Jardine, B. (2003). Theory and practical application of heat-pulse to measure sap flow. *Agronomy Journal* 5: 1371 – 1379.

Jones, G. R. (2012). Climate, Grapes, and Wine: Structure and Suitability in a Variable and Changing Climate In: *The Geography of Wine: Regions, Terrior, and Techniques*. (Editd by Dougherty, P.), Springer Press, USA. pp. 109 – 133.

Koundouras, S., Kanakis, I., Drossou, E., Kallithraka, S. and Kotseridis, Y. (2013). Influence of post-veraison water status on the phenolic composition of grapes and wines of cv. Agiorgitiko (*Vitis vinifera* L.) grown in Nemea. *International Journal of Science of Vine and Wine* 47(1): 115 – 128.

Kuhn, N., Guan, L. and Dai, Z. (2014). Berry ripening: recently heard through the grapevine. *Journal Experimental Botany* 65: 4543 – 4559.

Medrano, H., Tomas, M. and Martorell, S. (2015). Improving Water productivity of vineyards in semi-arid regions. *Agronomy Sustainable Development* 35(2): 499 – 519.

Mercker, D. F. (2011). *User Manual for Continuous Logging Probe.* Software Solution, Cape Town, South Africa. 20pp.

Mrosso, L. (2007). Development of vineyard cultivation in Dodoma. *Proceedings of Central Zone Agricultural Research Steering Committee Meeting*. Dodoma, Tanzania, 23 May, 2007. 14pp.

Ozden, M., Vardin, H., Simsek, M. and Karaaslan, M. (2010). Effects of rootstocks and irrigation levels on grape quality of *Vitis vinifera* L. cv. 'Shiraz'. *African Journal of Biotechnology* 9(25): 3801 – 3807.

Phogat, V., Skewes, M., McCarthy, M., Cox, J., Simunek, J. and Petrie, P. (2015). Evaluation of crop coefficients, water productivity, and water balance components for wine grapes irrigated at different deficit levels by a sub-surface drip. *Agricultural Water Management* 180: 22 – 34.

Rodriguez, V. M., Alberto, M. and Watts, C.. (2007). Antibacterial effect of phenolic compounds from different wines. *Food Control* 18: 93 – 101.

Seccia, A., Santeramo, F. and Nardone, G. (2015). Trade competitiveness in table grapes: A global view. [http://www.fabiosanteramo.net]site visited on 16/5/2016.

Stern, R., Buysse, W. and Coe, R. (2004). *GenStat Discovery Edition for Everyday Use*. International Centre for Research in Agroforestry, Nairobi, Kenya. 114pp.

Suvocarev, K., Blanco, O., Faci, J. and Medina, E. (2013). Transpiration of table grape (*Vitis vinifera*L.) trained on an overhead trellis system under netting. *Journal of Irrigation Science* 31: 1289 – 1302.

Teixeira, A., Bastiaanssen, W. and Bassoi, L. (2007). Crop water parameters of irrigated wine an table grapes to support water productivity analysis in the Sa˜o Francisco river basin. *Aquacultural Water Management* 94: 31 – 42.

Tomas, M., Medrano, H., Brugnoli, E., Escalona, J., Martorell, S. and Pou, A. (2014). Variability of mesophyll conductance in grapevine cultivars under water stress conditions in relation to leaf anatomy and water use efficiency. *Australian Journal of Grape Wine Research* 18: 164 – 172.

Williams, E., Grimes, D. and Phene, C. (2010). Effects of applied water at various fractions of measured evapotranspiration on reproductive growth and water productivity of (cv. 'Thompson seedless') grape vines. *Journal of Irrigation Science* 28: 233 – 243.

Zarrouk, O., Francisco, R., Pinto, M., Brossa, R., Santos, R. and Pinheiro, C. (2012). Impact of irrigation regime on berry development and flavonoids composition in Aragonez (cv. 'Tempranillo') grapes. *Agricultural Water Management* 114: 18 – 29.

Zerizghy, G. and Rensburg, L. (2013). Comparison of neutron scattering and capacitance instruments in measuring soil water evaporation. *Water South Africa* 39(2): 25 – 38.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The seasonal mean daily crop evapotranspiration (ET_c) for cv. 'Makutupora red' is 4.30 mm/day and the seasonal mean daily crop coefficient is 0.31. These values are for drip irrigation method at full irrigation. For other irrigation systems the vine transpiration (ET_b) will be the same but the evaporation (ET_e) must be adjusted to compensate for additional water losses (Teixeira *et al.,* 2007; Balint, 2011; Tagar *et al.,* 2012; Mahinda, 2014). The crop coefficient was 0.2, 0.32 and 0.29 at early, mid and final stages, respectively. It varies with berry and canopy development stages. The vines consume more water at mid stage than at initial and final stages of berry development. The coefficients at different stages are useful for estimating vines water requirement when weather data is used. The cultivar 'Makutupora red' is a drought resistant vine and suitable to be grown in semi-arid areas such as Dodoma Region. It has a lower crop coefficient (0.31) compared to other cultivars which have crop coefficients between 0.4 and 0.6 (Green *et al.,* 2007; Chaves *et al.,* 2010; Suvocarev *et al.,* 2013).

Grape quality was improved in all treatments subjected to deficit irrigation. Total soluble solids increased from 20 ^{o}Brix (at full irrigation) to between 23 and 25 ^{o}Brix by decreasing application of seasonal daily irrigation water from 4.30 mm/day (at full irrigation) to between 2.4 mm and 2.8 mm per day whereas grape yield decreased from 6.40 kg/vine (at full irrigation) to between 4.92 and 3.77 kg/vine. Increasing water deficits beyond 2.4 mm/day (severe irrigation deficit) causes great decrease in yield and water productivity. The use of deficit irrigation has the advantage of improving grape quality and minimizing irrigation water consumption in vines (Chaves *et al.,* 2010).

This fact is underscored by the response of cv. ‘Makutupora red’ by the improvement of its quality at moderate irrigation deficit while maintaining optimum yield. The Water productivity in treatments with moderate deficit irrigation regimes (V2M1) was improved by 24.4% compared to full treatments (V1M1). The Water productivity was low at full irrigation (when vines received sufficient water without deficit), then it increased to higher values at moderate deficit (at 63.5% of ET_c) and then decreased with increasing water deficit due to a decrease in grape yield.

Variations of grape quality and yield among irrigation methods were significant. In treatments with partial root zone drying (PRD) grape qualities were higher but grape yields were also significantly lower compared to root zone deficit rationing (RDR) and convention deficit irrigation (CDI). Convention deficit irrigation is more suitable for water use minimization and grape yield and quality optimization than partial root zone drying (PRD) and root zone deficit rationing (RDR).

Grape yield was positively correlated fruit weight, fruit diameter, cluster weight, pruned mass and leaf area index which decreased with a decrease in the amount of irrigation water supplied to the vines and negatively correlated to total soluble solids, phenols, anthocyanins and alcohol content which increased with a decrease in the amount of irrigation applied to the vines. There are other factors that affect grape yield and quality (Chaves *et al*., 2010). Uniform control and management (such as pruning, fertilizer application, disease control, weeding) of the vines was important during this study for ensuring that the response of cv. ‘Makutupora red’ to its yield and quality was only due to subjection of the vines to different irrigation regimes.

5.2 Recommendations

For grapes cv. ‘Makutupora red’ grown in Dodoma the use of vine crop coefficients is recommended depending on the berry and canopy development stages. At initial stage the mean daily crop coefficient K_c is 0.20, at mid stage K_c is 0.38 and at final stage K_c is 0.27.

The use of deficit drip irrigation is recommended as a suitable method for improving grape quality. Conventional drip irrigation method is recommended to be the best option at 63.5% and 56.3% of crop evapotranspiration (ET_c) because of its high water productivity, high Water productivity by quality, high grape quality and optimum grape yield.

Grape growers in Dodoma using drip irrigation can improve the grape quality by rectifying their irrigation schedules so that irrigation deficits are applied according to the suggested rates of treatments V2M1 and V3M1. Timely deficit applications in vineyards are important as the vine water consumption varies with berry development stages.

The recommended crop coefficients and deficit levels are for cv. ‘Makutupora red’ under drip irrigation. If deficit irrigation is to be used in other irrigation systems, the adjustment of evaporation component ET_e which was only 8.88% of vines evapotranspiration (ET_c) under drip irrigation will be required. Further studies are recommended for determining vine crop water requirement and investigating the response to deficit irrigation for other V*itis vinifer*a L. cultivars which are grown in Dodoma Region such as ‘Makutupora white’, ‘Chenin blanc’, ‘Black rose’ and ‘Ruby seedless’

5.3 References

Balint, G. (2011). Impact of different irrigation strategies on grapes and wine quality of four grapevine cultivars (Vitis sp.) in cool climate conditions. An investigation into the relationships among, water status, grape cultivar and wine quality. Thesis for Award of PhD Degree at Brock University, St. Catherines Ontanario, Canada, 429pp.

Chaves, M. M., Francisco, R., Costa, J., Santos, T., Regalado, A. P., Rodrigues, M. (2010). Grapevine under deficit irrigation: hints from physiological and molecular data. *Annals of Botany* 105: 661 – 676.

Green, S., Clothier, B. and Deurer, M. (2007). Measuring and modeling stress response of grapevines to soil-water deficits. In: *Understanding and Modeling Water Stress Effects on Plant Growth Processes.* (Edited by Davidson, P.), The Horticulture and Food Research Institute, New Zealand. pp. 357 – 385.

Mahinda, A. (2014). Effect of drip irrigation on the production and economic returns of soghurm in semi arid areas of Tanzania. Nairobi, Kenya. Dissertation for Award of MSc Degree at University of Nairobi, Kenya, 94pp.

Tagar, A., Chandio, F. A., Mari, I. A. and Wagan, B. (2012). Comparative study of drip and furrow irrigation methods at farmer's field in Umarkot. *International Journal of Biological, Biomolecular, Agricultural, Food and Biotechnological Engineering* 6(9): 788 – 792.

Suvocarev, K., Blanco, O., Faci, J. and Medina, E. (2013). Transpiration of table grape (Vitis vinifera L.) trained on an overhead trellis system under netting. *Journal of Irrigation Science* 31: 1289 – 1302.

Teixeira, A. H. C. (2007). Crop water parameters of irrigated wine and table grapes to support water productivity analysis in the Sa˜o Francisco river basin. *Agricultural Water Management* 94: 31 – 42 .

APPENDICES

Appendix 1: Sap flow and soil moisture probes

Connections of sap flow probes to the logger

Soil moisture probe in a cage

Appendix 2: Correlation among yield and quality components

Correlation among yield and quality components in season 2014

Yield	1.000															
LAI	0.650															
PM	0.599	0.532														
Bd	0.714	0.412	0.534													
Bw	0.613	0.558	0.307	0.546												
Cw	0.649	0.347	0.284	0.532	0.620											
CN	0.545	0.244	0.447	0.346	0.183	0.237										
TSS	-0.848	-0.546	-0.595	-0.749	-0.620	-0.768	-0.437									
Alco	-0.849	-0.579	-0.602	-0.747	-0.613	-0.761	-0.401	0.991								
TTA	0.228	0.224	0.181	0.236	0.132	0.182	0.242	-0.254	-0.228							
T_T	-0.756	-0.528	-0.528	-0.695	-0.550	-0.686	-0.435	0.898	0.878	-0.650						
pH	0.567	0.326	0.392	0.465	0.465	0.437	0.127	-0.561	-0.589	-0.015	-0.429					
phenol	-0.861	-0.538	-0.627	-0.759	-0.626	-0.781	-0.437	0.989	0.988	-0.222	0.872	-0.614				
Anth	-0.857	-0.530	-0.637	-0.764	-0.629	-0.777	-0.421	0.969	0.973	-0.191	0.843	-0.661	0.994			
Tar	-0.244	-0.163	-0.017	-0.162	-0.294	-0.218	-0.172	0.150	0.150	0.082	0.087	-0.263	0.151	0.142		
Mal	0.142	0.124	0.280	0.270	0.137	0.038	0.169	-0.256	-0.243	-0.040	-0.173	0.264	-0.261	-0.281	0.386	1.000
	Yield	**LAI**	**PM**	**Bd**	**Bw**	**Cw**	**CN**	**TSS**	**Alco**	**TTA**	**T/T**	**pH**	**phenol**	**Anth**	**Tar**	**Mal**

Where yield = grape yield kg/vine, LAI = Leaf area index, Pm = Pruned mass g/vine, Cw = cluster weight g, Bd = berry diameter cm, Bw = berry weight g, TSS = grape juice total soluble solids °Brix, TTA = Total titratable acids g/*l*, T/T = The ratio of total soluble solids to the total titratable acids, Alco = alcohol percentage of wine after fermentation of grape juice %, Phenol = phenol concentration in the grape juice g/l, Anth = concentration of anthocyanins in the grape juice mg/l. Tar = Tartaric acid g/l, Ma = Malic acid g/l.

Correlation among yield and quality components in season 2015

yield	1.000															
LAI	0.261															
Pm	0.505	0.576														
Bd	0.500	0.414	0.673													
Bw	0.452	0.492	0.531	0.496												
Cw	0.701	0.575	0.702	0.596	0.611											
CN	0.495	0.223	0.325	0.458	0.307	0.446										
TSS	-0.707	-0.416	-0.447	-0.391	-0.482	-0.716	-0.539									
Alco	-0.731	-0.333	-0.430	-0.372	-0.506	-0.713	-0.550	0.957								
TTA	0.469	0.163	-0.018	0.087	0.235	0.341	0.186	-0.316	-0.368							
T/T	-0.739	-0.361	-0.290	-0.326	-0.442	-0.664	-0.474	0.824	0.833	-0.785						
pH	0.327	0.094	0.278	0.307	0.248	0.157	0.211	-0.230	-0.239	0.121	-0.211					
Phenol	-0.805	-0.406	-0.546	-0.444	-0.554	-0.791	-0.529	0.946	0.967	-0.403	0.851	-0.320				
anth	-0.799	-0.401	-0.559	-0.456	-0.557	-0.793	-0.528	0.944	0.963	-0.377	0.833	-0.331	0.998			
Tar	0.229	0.096	-0.079	-0.033	0.139	0.146	-0.012	-0.119	-0.161	0.752	-0.494	-0.074	-0.155	-0.124		
Mal	0.299	0.129	-0.019	0.012	0.197	0.221	0.042	-0.217	-0.268	0.748	-0.550	-0.009	-0.253	-0.227	0.972	1.000
	yield	**LAI**	**Pm**	**Bd**	**Bw**	**Cw**	**CN**	**TSS**	**Alco**	**TTA**	**T/T**	**pH**	**Phenol**	**anth**	**Tar**	**Mal**

Where yield = grape yield kg/vine, LAI = Leaf area index, Pm = Pruned mass g/vine, Cw = cluster weight g, Bd = berry diameter cm, Bw = berry weight g, TSS = grape juice total soluble solids °Brix, TTA = Total titratable acids g/*l*, T/T = The ratio of total soluble solids to the total titratable acids, Alco = alcohol percentage of wine after fermentation of grape juice %, Phenol = phenol concentration in the grape juice g/l, Anth = concentration of anthocyanins in the grape juice mg/l. Tar = Tartaric acid g/l, Ma = Malic acid g/l.

Appendix 3: Experiment lay out