UNIVERSITI PUTRA MALAYSIA

GROWTH, WATER RELATION, YIELD AND CROP QUALITY OF ARABICA COFFEE IN RESPONSE TO WATER STRESS AND DEFICIT IRRIGATION

TESFAYE SHIMBER GESSESE.

FP 2006 6
GROWTH, WATER RELATION, YIELD AND CROP QUALITY OF ARABICA COFFEE IN RESPONSE TO WATER STRESS AND DEFICIT IRRIGATION

By

TESFAYE SHIMBER GESSESE

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

February 2006
DEDICATION

This manuscript is dedicated to my beloved parents, Ato Shimber Gessese and W/o Ayelech Degu, to my wife, W/o Sara Alemu and my children, Emnet Tesfaye, Amanuel Tesfaye and Metsenanat Tesfaye.
Coffee (Coffea Arabica L.) is the single most important commodity crop that comes after petroleum in the world market. It plays a significant role in the economy of Ethiopia, contributing over 60% of the nation’s foreign exchange earnings, 30% of the government’s direct revenue, 8% output of the agricultural sector and 4% of the gross domestic production. In spite of the importance of the crop in the country’s economy, its average national yield is very low primarily because of traditional production technologies. Apart from hereditary characteristics of the trees, seasonal water stress and recurrent drought are among the major factors which account for low yields of the crop in most coffee growing regions of the country. In the present study, attempt was made to identify water stress tolerant Arabica coffee cultivars and deficit irrigation practices that could improve growth, yield, quality and water use efficiency of the crop under both protected environment and field condition in Ethiopia. Both rain shelter and field experiments were carried out in a randomized complete block design with three replications in the rain shelter and four replications in the field. In the first rain shelter
than NDI for coffee production particularly in areas where water is scarce and dry spells are prolonged. On the other hand, the effect of supplemental deficit irrigation on plant water relations, crop yield and quality was studied in the field using young coffee stands of three cultivars (F-59, 74110 and 75227). Two irrigation treatments, namely, supplemental full irrigation (SFI) and supplemental deficit irrigation (SDI), applied in the conventional way, were compared against rain fed (RF) control. SFI consistently increased soil moisture content, leaf RWC and $g_s$ during the dry period, but there was no difference between the treatments in the main wet season. Besides, SFI significantly increased coffee yield, but the difference between SFI and SDI was not significant and yet SDI had 21 – 24% yield advantage over the RF treatment. On the other hand, overall quality of coffee beans was considerably increased by SDI and RF treatments. Therefore, SDI seems to be more effective than SFI and it can be used as an option next to PRD for coffee production in drier areas.
study, twenty four known cultivars, which are indigenous to the country, were subjected to a soil drying treatment to identify those tolerant genotypes. Variations among the cultivars for mean stress scores, rate of recovery from drought, root to shoot ratio, concentration of inorganic solutes (K, Ca and Mg) in leaves, specific leaf area and survival rate showed that some of the genotypes, such as 74110, 74112 and 8/85, were less sensitive to water stress at seedling stage. On the other hand, in an experiment where three irrigation regimes (well watering, WW, normal deficit irrigation, NDI, and partial root zone drying, PRD) were studied on cultivar F-59 grown in a rain shelter, it was found that NDI and PRD reduced shoot growth, total dry matter production, dry weights of leaves, stem and roots, leaf relative water content (RWC) and stomatal conductance \( g_s \), but increased root to shoot ratio and irrigation water use efficiency (IWUE) of coffee seedlings. Therefore, it was concluded that PRD is an effective deficit irrigation practice to increase IWUE and decrease irrigation water requirement by 50% without substantial adverse effects on plant growth and development, and it could be practically advantageous in coffee nurseries especially in areas of water scarcity and prolonged drought periods. The same study was carried out in the field to determine the effect of PRD on plant water relations and crop yield and quality of Arabica coffee. Results of the field experiment also indicated that leaf RWC, \( g_s \), fruit growth rate and some yield components were reduced by both PRD and NDI. However, the difference between WW and PRD was not significant for crop yield and yet PRD resulted in over 41% more IWUE than the WW treatment, reduced the amount of irrigation water by 50% and considerably improved both raw and liquor quality of coffee beans. Hence, it was concluded that PRD can be a feasible irrigation strategy, which can save irrigation water, increase IWUE and maintain crop yield, and it appears to be more advantageous.
Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PERTUMBUHAN, KAITAN AIR, HASIL DAN KUALITI TANAMAN KOPI ARABICA TERHADAP KEKURANGAN AIR DAN PENGAIRAN DEFICIT

Oleh

TESFAYE SHIMBER GESSESE

February 2006

Pengerusi : Profesor Madya Mohd. Razi Ismail, PhD
Fakulti : Pertanian

Kopi (Coffea Arabica L.) merupakan satu-satunya tanaman komoditi terpenting selepas petroleum dalam pasaran dunia. Ia memainkan peranan penting dalam ekonomi Ethiopia, yang menyumbang lebih 60% pertukaran pendapatan bangsa asing, 30% pulangan langsung kerajaan, 8% keluaran sektor pertanian dan 4% pulangan langsung pengeluaran kerajaan. Halangan utama tanaman ini dalam ekonomi Negara adalah purata hasil penduduk yang sangat rendah terutamanya disebabkan oleh teknologi pengeluaran secara tradisional. Ciri-ciri pokok asing yang diwarisi, musim kekurangan air dan kemarau yang berulang merupakan faktor utama yang menyumbang kepada hasil tanaman yang rendah terutamanya tanamna kopi serantai di Negara ini. Dalam kajian ini, usaha dilakukan untuk mengenalpasti kultivar kopi Arabica yang tahan terhadap kekurangan air dan amalan pengurangan pengairan yang dapat memperbaiki pertumbuhan, hasil, kualiti dan keefisienan penggunaan air tanaman dalam keadaan persekitaran terkawal dan di lading di Ethiopia. Kajian di bawah rumah lindungan hujan dan di ladang dilakukan dengan rekabentuk rawak lengkap berblok dengan tiga kali ulangan dalam rumah lindungan hujan dan empat kali ulangan di ladang. Kajian pertama...
dijalankan di dalam rumah lindungan hujan, sebanyak 24 kultivar yang diketahui, yang berasal dari negara ini, dikenakan rawatan untuk mengenalpasti genotaip yang tahan terhadap pengeringan tanah. Variasi antara kultivar yang mendapat purata tekanan, kadar pulih semula dari kemarau, nisbah akar ke pucuk, kepekatan larutan inorganic (K, Ca dan Mg) dalam daun, luas daun spesifik dan kadar ketahanan menunjukkan terdapat beberapa genotaip seperti 74110, 74112 dan 8/85, kurang sensitif terhadap kekurangan air pada tahap biji benih. Dalam keadaan lain, satu kajian di mana tiga regim pengairan (pengairan baik, WW, pengairan defisit biasa, NDI dan pengeringan sebahagian zon akar, PRD) dikaji ke atas kultivar F-59 yang ditanam di dalam rumah lindungan hujan dan didapati bahawa NDI and PRD mengurangkan pertumbuhan pucuk, jumlah penghasilan berat kering, berat kering daun, batang dan akar, kandungan relatif air daun (RWC) dan kondultiviti stomata (gs), tetapi meningkatkan nisbah akar ke pucuk dan pengairan air secara efisien pada biji benih kopi. Oleh itu, disimpulkan bahawa PRD merupakan amalan pengairan deficit yang efektif untuk meningkatkan IWUE dan mengurangkan keperluan pengairan air kepada 50% tanpa kesan kerugian yang banyak ke atas perkembangan dan pertumbuhan tanaman dan ia boleh menjadi amalan yang berfaedah dalam tapak semaian kopi terutamanya dalam kawasan kekurangan air dan tempoh kemarau yang panjang. Kajian yang sama juga dijalankan di ladang untuk mengenalpasti kesan PRD ke atas perkaitan air tanaman, hasil tanaman dan kualiti kopi Arabica. Keputusan kajian di ladang juga menunjukkan kandungan relatif air daun, gs, kadar pertumbuhan buah dan beberapa komponen hasil berkurangan dengan rawatan PRD dan NDI. Walau bagaimanapun, tiada perbezaan yang bererti antara WW and PRD bagi hasil tanaman dan keputusan menunjukkan lebih 40% lebih IWUE dari rawatan WW, mengurangkan jumlah pengairan air sebanyak 50% dan peningkatan yang tinggi
terhadap kualiti bahan mentah dan kualiti minuman biji kopi. Dengan itu, disimpulkan bahawa strategi pengaran secara PRD boleh dilaksanakan untuk menjimatkan pengairan air, meningkatkan hasil tanaman dan ia dilihat lebih banyak memberi faedah berbanding NDI untuk pengeluaran kopi terutamanya dalam kawasan kekurangan air dan jangkamasa kering yang yang panjang. Dalam kajian yang lain, kesan pemberian pengairan yang kurang ke atas perkaitan air tanaman, hasil tanaman dan kualiti di kaji di ladang menggunakan anak benih kopi yang terdiri daripada kultivar (F-59, 74110 dan 75227). Dua rawatan pengairan iaitu pemberian pengairan penuh (SFI) dan pemberian pengairan kurang (SDI) diaplikasikan mengikut kaedah yang biasa diamalkan, dibandingkan dengan air hujan (RF) sebagai kawalan. SFI secara tetap meningkatkan kandungan lembapan tanah, kandungan relatif air dan $g_s$ sepanjang jangkamasa kering, tetapi tiada beza secara bererti dengan rawatan dalam musim lembap yang utama. Di samping itu, SFI meningkatkan hasil kopi secara bererti, tetapi perbezaan antara SFI dan SDI tidak berbeza secara bererti dengan SDI memperoleh 21-24% faedah hasil lebih daripada rawatan RF. Dengan erti kata lain, kualiti keseluruhan biji kopi telah meningkat dengan banyak dengan rawatan SFI dan RF. Sementara itu, SDI kelihatan lebih efektif berbanding SFI dan ia boleh digunakan sebagai pilihan selain daripada PRD untuk pengeluaran kopi dalam kawasan kering.
ACKNOWLEDGEMENTS

My deep gratitude goes to the chairman of my supervisory committee, Associate Professor Dr. Mohd Razi Bin Ismail for his invaluable advice, constant guidance and encouragement throughout execution of the experiments and write-up of the manuscript. I am also indebted to my supervisory committee members, Professor Marziah Mahmood and Associate Professor Dr. Mohd Fauzi Ramlan for their unreserved guidance, constructive criticism and encouragement in the course of my study.

I am grateful to the staff and technicians of Hydroponics Unit and Plant Physiology Section of Department of Crop Science, Faculty of Agriculture, UPM. I would like to express my sincere appreciation to Mr. Ismail Bin Iberahim, Dr. Hassan Ibrahim Ali and Mrs. Siti Zaharah for their encouragement and technical assistance. I am also grateful to my friends and Ethiopian colleagues for their encouragement and technical assistance in the course of my study in Malaysia.

Special thanks are due to Ato Million Abebe for his support and encouragement in the course of my study. I fully acknowledge Ato Alemseged Yilma, Ato Teshome Kumela, Ato Bekele Bogale, Ato Shimelis W/Ab, Ato Nigussie Mekonen, Ato Behailu W/Senbet, W/o Elfinesh Triro and Ato Dereje G/Georgis for their unceasing support and technical assistance in the field and laboratory activities in Ethiopia. The unreserved support and constant encouragement of my friends Alazar Assefa, Demelash Teferi, Worku Demmissie and Aregash Samuel is greatly appreciated.
The completion of this work would have been impossible without the endless patience and dedication of my children, Emenet Tesfaye, Amanuel Tesfaye and Metsinanat Tesfaye, and my wife W/o Sara Alemu to endure loneliness in my absence.

I express my sincere appreciation to the Ethiopian Agricultural Research Organization (EARO), Agricultural Research and Training Project (ARTP) for sponsoring my study and the Jima Agricultural Research Center (JARC) for its unreserved assistance in providing me with the necessary materials, facility and manpower in the course of the study. I would like to express my gratitude to Sheno Agricultural Research Center for the provision of some important scientific equipments, mainly porometer, in Ethiopia.
# Table of Contents

**DEDICATION**  
**ABSTRACT**  
**ABSTRAK**  
**ACKNOWLEDGEMENTS**  
**APPROVAL**  
**DECLARATION**  
**LIST OF TABLES**  
**LIST OF FIGURES**  
**LIST OF ABBREVIATIONS AND SYMBOLS**

## Chapter 1: Introduction

## 2 Literature Review

2.1 Water Deficit and Leaf Gas Exchange  
2.1.1 Plant Water Status  
2.1.2 Stomatal Behavior  
2.2 Accumulation of Inorganic Solutes  
2.3 Plant Growth Responses to Drought  
2.3.1 Shoot and Root Extension Growth  
2.3.2 Dry Matter Yield and Partitioning  
2.3.3 Crop Yield and Quality  
2.4 Deficit Irrigation and Crop Productivity  
2.4.1 The Need for Deficit Irrigation  
2.4.2 Deficit Irrigation Techniques  
2.4.3 Plant Response to Deficit Irrigation

## 3 General Materials and Methods

3.1 Determination of Field Capacity of Soils  
3.2 Measurement of Plant Water Status  
3.2.1 Relative Leaf Water Content  
3.2.2 Stomatal Conductance  
3.3 Vegetative Growth Parameters  
3.3.1 Leaf Growth  
3.3.2 Stem and Branch Growth  
3.3.3 Root Growth  
3.4 Dry Matter Production  
3.4.1 Total Dry Matter Yield  
3.4.2 Dry Matter Partitioning  
3.5 Crop Yield and Yield Components  
3.5.1 Fruit Growth  
3.5.2 Crop Yield

xiv
3.6 Coffee Quality Determination
3.6.1 Coffee Processing
3.6.2 Grading and Roasting
3.6.3 Cup Preparation and Tasting
3.7 Measurement of Soil Moisture Content
3.8 Irrigation Water Use Efficiency
3.9 Statistical Analysis

4 PHYSIOLOGICAL AND MORPHOLOGICAL RESPONSES OF ARABICA COFFEE (COFFEA ARABICA L.) GENOTYPES TO SOIL DRYING
4.1 Introduction
4.2 Materials and Methods
4.2.1 Plant Materials
4.2.2 Treatments and Plot Arrangement
4.2.3 Stress Rating
4.2.4 Rate of Survival and Leaf Shed
4.2.5 Rate of Recovery
4.2.6 Plant Water Relations
4.2.7 Determination of K, Ca and Mg in Coffee Leaves
4.2.8 Plant Growth Parameters
4.2.9 Statistical Analysis
4.3 Results
4.3.1 Stress Score
4.3.2 Percent Plant Wilting and Recovering
4.3.3 Rate of Survival and Leaf Shed
4.3.4 Overall Sensitivity
4.3.5 Leaf Relative Water Content
4.3.6 Stomatal Conductance
4.3.7 Leaf K, Ca and Mg Content
4.3.8 Leaf and Root Growth
4.3.9 Dry Matter Yield and Partitioning
4.3.10 Rate of Recovery
4.4 Discussion
4.4.1 Sensitivity to Water Stress
4.4.2 Leaf Relative Water Content
4.4.3 Stomatal Conductance
4.4.4 Leaf K, Ca and Mg Content
4.4.5 Leaf and Root Growth
4.4.6 Dry Matter Yield and Partitioning
4.4.7 Rate of Recovery
4.5 Conclusion
5 GROWTH AND PLANT WATER RELATIONS OF ARABICA COFFEE SEEDLINGS IN RESPONSE TO PARTIAL ROOTZONE DRYING

5.1 Introduction

5.2 Materials and Methods
   5.2.1 Plant Material and Media Potting
   5.2.2 Treatments and Experimental Design
   5.2.3 Determination of Soil Moisture Content
   5.2.4 Leaf Relative Water Content
   5.2.5 Stomatal Conductance
   5.2.6 Vegetative Growth Parameters
   5.2.7 Dry Matter Production and Partitioning
   5.2.8 Irrigation Water Use Efficiency
   5.2.9 Statistical Analysis

5.3 Results
   5.3.1 Soil Moisture Content
   5.3.2 Leaf Relative Water Content
   5.3.3 Stomatal Conductance
   5.3.4 Vegetative Growth
   5.3.5 Dry Matter Production and Partitioning
   5.3.6 Irrigation Water Use Efficiency

5.4 Discussion
   5.4.1 Soil Moisture Content
   5.4.2 Leaf Relative Water Content
   5.4.3 Stomatal Conductance
   5.4.4 Vegetative Growth
   5.4.5 Dry Matter Production and Partitioning
   5.4.6 Irrigation Water Use Efficiency

5.5 Conclusion

6 EFFECT OF PARTIAL ROOT ZONE DRYING ON PLANT WATER RELATIONS, CROP YIELD AND QUALITY OF ARABICA COFFEE

6.1 Introduction

6.2 Materials and Methods
   6.2.1 Site Description
   6.2.2 Plant Materials
   6.2.3 Plot Arrangement
   6.2.4 Irrigation Treatments
   6.2.5 Measurement of Water Relations
   6.2.6 Crop Yield and Quality Analysis
   6.2.7 Irrigation Water Use Efficiency
   6.2.8 Statistical Analysis

6.3 Results
   6.3.1 Soil Moisture Content
   6.3.2 Leaf Relative Water Content
   6.3.3 Stomatal Conductance
   6.3.4 Fruit Growth Rate
   6.3.5 Yield Components
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Standard parameters and their respective values used for coffee quality evaluation</td>
<td>52</td>
</tr>
<tr>
<td>4.1</td>
<td>Mean stress score value for coffee cultivars under water-stressed (WS) condition on different days from start of treatment application</td>
<td>61</td>
</tr>
<tr>
<td>4.2</td>
<td>Mean percent plants wilting (PPW) at noon, rate of leaf shed (RLS) and rate of survival (RS) in coffee cultivars under water stress (WS) condition</td>
<td>64</td>
</tr>
<tr>
<td>4.3</td>
<td>Mean percent plants recovering (PPR) during the night time and mean days to complete wilting (MDCW) of plants of different coffee cultivars under water stress (WS) conditions</td>
<td>65</td>
</tr>
<tr>
<td>4.4</td>
<td>Relationship between leaf K, Ca and Mg concentration, SLA, total leaf area (TLA), root volume (RV), root:shoot ratio (RSR), stress score (SS) and rate of recovery (RR) (Correlation matrix using Pearson Correlation Coefficients)</td>
<td>76</td>
</tr>
<tr>
<td>5.1</td>
<td>Vegetative growth of coffee seedlings in response to varying irrigation regimes (WW = well-watered, PRD = partial root zone drying and NDI = normal deficit irrigation)</td>
<td>111</td>
</tr>
<tr>
<td>6.1</td>
<td>Effect of irrigation regime on raw and cup quality of coffee beans (WW = well-watering, PRD = partial root zone drying and NDI = normal deficit irrigation)</td>
<td>144</td>
</tr>
<tr>
<td>6.2</td>
<td>Size distribution (SD) and mean weight (MW) of coffee beans as affected by irrigation regime (WW = well-watering, PRD = partial root zone drying and NDI = normal deficit irrigation)</td>
<td>144</td>
</tr>
<tr>
<td>7.1</td>
<td>Effect of supplemental irrigation (supplemental full irrigation (SFI), supplemental deficit irrigation (SDI) and rain fed (RF)) on raw and cup quality of coffee beans</td>
<td>174</td>
</tr>
<tr>
<td>7.2</td>
<td>Size distribution (SD) and mean weight (MW) of coffee beans as affected by supplemental irrigation (supplemental full irrigation (SFI), supplemental deficit irrigation (SDI) and rain fed (RF)</td>
<td>174</td>
</tr>
</tbody>
</table>
A1 Analysis of Variance Procedure (Mean Square values) for the variables considered during screening of Arabica coffee cultivars for drought tolerance in a randomized complete block design in a rain shelter

A2 Analysis of Variance Procedure for variables used to study the mechanism of drought tolerance in selected Arabica coffee genotypes arranged in a randomized complete block design with two watering regimes and 12 cultivars in a rain shelter

A3 Analysis of Variance Procedure (Mean square values) for growth parameters of Arabica coffee seedlings under deficit irrigation treatments in randomized complete block design in a rain shelter

A4 Analysis of Variance Procedure (Mean square values) for coffee yield, yield components and crop quality of field deficit irrigation treatments in a randomized complete block design (Cv. F-59)

A5 Analysis of Variance Procedure (Mean Square values) for yield, yield components and crop quality of field supplemental irrigation experiment: Cv. F-59 in a randomized complete block design and Cv. 75227 and Cv. 74110 in a split plot design
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Picture depicting different growth stages of Arabica coffee fruits on branches of crop bearing trees</td>
<td>47</td>
</tr>
<tr>
<td>4.1</td>
<td>Screening Arabica coffee genotypes for drought tolerance in a rain shelter and the corresponding 1 – 5 scale stress score values</td>
<td>57</td>
</tr>
<tr>
<td>4.2</td>
<td>Leaf relative water content (RWC) of Arabica coffee cultivars as affected by soil drying (open symbols represent water-stressed and closed symbols well-watered plants).</td>
<td>68</td>
</tr>
<tr>
<td>4.3</td>
<td>Stomatal conductance ($g_s$) of Arabica coffee cultivars as affected by soil drying (open symbols represent water-stressed and closed symbols well-watered plants).</td>
<td>69</td>
</tr>
<tr>
<td>4.4</td>
<td>Concentration of potassium (K), calcium (Ca) and magnesium (Mg) ions in leaves of different coffee cultivars grown under well-watered and water-stressed conditions.</td>
<td>70</td>
</tr>
<tr>
<td>4.5</td>
<td>Mean leaf elongation rate (LER), total leaf area (LA), specific leaf area (SLA) and root volume of coffee seedlings under well-watered and water-stressed conditions.</td>
<td>71</td>
</tr>
<tr>
<td>4.6</td>
<td>Leaf, stem and root dry weight (DW) and total dry matter (TDM) yield of seedlings of different Arabica coffee cultivars under well-watered and water-stressed conditions.</td>
<td>73</td>
</tr>
<tr>
<td>4.7</td>
<td>Root:shoot ratio of seedlings of different Arabica coffee cultivars under well-watered and water-stressed conditions.</td>
<td>74</td>
</tr>
<tr>
<td>4.8</td>
<td>Percent reduction in total leaf area (TLA) and total dry matter yield (TDM) due to soil drying and rate of recovery after rewatering of seedlings of different Arabica coffee cultivars.</td>
<td>75</td>
</tr>
<tr>
<td>5.1</td>
<td>Picture depicting partial root zone drying (PRD) practice applied on Arabica coffee seedlings grown in a rain shelter</td>
<td>101</td>
</tr>
<tr>
<td>5.2</td>
<td>Soil moisture content (SMC) of potted coffee seedlings (cv. F-59) as affected by deficit irrigation in a rain shelter (WW = well-watered, NDI = normal deficit irrigation, PRD = partial root zone drying).</td>
<td>107</td>
</tr>
<tr>
<td>5.3</td>
<td>Leaf relative water content (RWC) of coffee seedlings (cv. F-59) as affected by deficit irrigation in a rain shelter (WW = well-watered, NDI = normal deficit irrigation, PRD = partial root zone drying).</td>
<td>108</td>
</tr>
</tbody>
</table>
5.4 Stomatal conductance \((g,)\) of coffee seedlings (cv. F-59) grown in a rain shelter as affected by deficit irrigation (WW = well-watered, NDI = normal deficit irrigation, PRD = partial root zone drying). 109

5.5 Leaf elongation rate (LER) in coffee seedlings (cv. F-59) as affected by deficit irrigation in a rain shelter (WW = well-watered, PRD = partial root zone drying, and NDI = normal deficit irrigation). 110

5.6 Total dry matter (TDM) yield and its partitioning among leaves, stem and roots, root:shoot ratio and irrigation water use efficiency (IWUE) of coffee seedlings (cv. F-59) as affected by deficit irrigation (WW = well-watered, PRD = partial root zone drying, and NDI = normal deficit irrigation). 113

6.1 Weekly mean air temperature, total rainfall and mean relative humidity at JARC (measurements were taken between September 8, 2003 and September 2, 2004). 128

6.2 Picture depicting field partial root zone drying (PRD) practice on young Arabica coffee trees 130

6.3 Soil moisture content as affected by deficit irrigation in a coffee stand (cv. F-59) (WW = well watering, NDI = normal deficit irrigation and PRD = partial root zone drying). 135

6.4 Leaf relative water content (RWC) of coffee plants (cv. F-59) as affected by deficit irrigation (WW = well watering, NDI = normal deficit irrigation and PRD = partial root zone drying). 136

6.5 Stomatal conductance \((g,)\) of coffee plants (cv. F-59) as affected by deficit irrigation (WW = well watering, NDI = normal deficit irrigation and PRD = partial root zone drying). 137

6.6 Effect of deficit irrigation on growth and development of coffee berries. Fruit growth stages involve pin head stage (PHS); rapid fruit growth stage (RFGS); endosperm growth stage (ESGS) and endosperm hardening stage (ESHS) on three measurement occasions (I. 10, II. 16, III. 22 weeks after the commencement of treatment application). Irrigation treatments were well-watered (WW) control; partial root zone drying (PRD) and normal deficit irrigation (NDI). 139

xxi
Yield components of Arabica coffee (cv. F-59) as affected by deficit irrigation (WW = well-watered; PRD = partial root zone drying and NDI = normal deficit irrigation): a) number of flowering branches tree\(^{-1}\) (NFRBPT); b) number of flowers branch\(^{-1}\) (NFLPB); c) number of fruits branch\(^{-1}\) (NFRPB); d) flower to fruit ratio (FLFRR); e) number of fruits tree\(^{-1}\) (NFRPT) and, f) fresh cherry yield (FCY).

Effect of irrigation regime on fruit loss at different berry development stages in Arabica coffee (cv. F-59): a) loss of fruit set after flowering, b) loss of fruits during pin head stage, c) loss of fruits at rapid growth stage, d) loss of fruits during endosperm growth stage, e) loss of fruit set from flowering up to endosperm development, and f) loss of fruits from pin head to endosperm development stage.

Fresh cherry yield and irrigation-water-use efficiency (IWUE) of coffee plants (cv. F-59) as affected by deficit irrigation: well-watered (WW); partial root zone drying (PRD) and normal deficit irrigation (NDI).

Overall raw and liquor and total quality of coffee beans as affected by different irrigation treatments: well-watered (WW), partial root zone drying (PRD) and normal deficit irrigation (NDI).

Picture depicting field plot arrangement for conventional deficit irrigation practice on young Arabica coffee trees

Soil moisture content (SMC) as affected by supplemental irrigation in a coffee stand (cv. F-59) during the dry season (SFI = full irrigation when the soil moisture content declines to < 35% of FC, SDI = supplemental deficit irrigation with half of the amount applied to SFI, RF = rain fed control).

Leaf relative water content (RWC) as affected by supplemental irrigation in a coffee stand (cv. F-59) during the dry season (SFI = full irrigation when the soil moisture content declines to < 35% of FC, SDI = supplemental deficit irrigation with half of the amount applied to SFI, RF = rain fed control).

Stomatal conductance \((g_s)\) of coffee plants (cv. F-59) as affected by supplemental irrigation during the dry season (SFI = full irrigation when the soil moisture content declines to < 35% of FC, SDI = supplemental deficit irrigation with half of the amount applied to SFI, RF = rain fed control).
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>Effect of conventional irrigation on number of fruits and fresh cherry yield tree(^{-1}) of two coffee cultivars (cv. 75227 and cv. 74110). Irrigation treatments involved supplemental deficit irrigation (SDI) and rain fed (RF).</td>
</tr>
<tr>
<td>7.6</td>
<td>Effect of conventional irrigation (supplemental full irrigation (SFI), supplemental deficit irrigation (SDI) and rain fed (RF)) on yield of three coffee cultivars (cv. F-59, 75227 and 74110).</td>
</tr>
<tr>
<td>7.7</td>
<td>Overall raw and liquor and total qualities of coffee beans as affected by conventional irrigation practices: supplemental full irrigation (SFI), supplemental deficit irrigation (SDI) and rain-fed (RF) treatments.</td>
</tr>
<tr>
<td>A1</td>
<td>Screening Arabica coffee genotypes for drought tolerance in a rain shelter at JARC, Ethiopia (plot arrangement)</td>
</tr>
<tr>
<td>A2</td>
<td>Picture depicting partial root zone drying (PRD) practice applied on Arabica coffee seedlings grown in a rain shelter</td>
</tr>
<tr>
<td>A3</td>
<td>Growth differences between coffee seedlings under well-watered (WW), partial root zone drying (PRD) and normal deficit irrigation (NDI) conditions</td>
</tr>
<tr>
<td>A4</td>
<td>Pictures depicting field partial root zone drying (PRD) practice on young Arabica coffee trees</td>
</tr>
<tr>
<td>A5</td>
<td>Picture depicting field conventional deficit irrigation practice on young Arabica coffee trees</td>
</tr>
<tr>
<td>A6</td>
<td>Pictures depicting different growth stages of Arabica Coffee fruits on the same crop bearing tree</td>
</tr>
<tr>
<td>A7</td>
<td>Coffee beans at different processing stages, cup preparation and cup tasting for liquor quality of coffee samples harvested from different field irrigation treatments</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Symbol</td>
</tr>
<tr>
<td>--------------</td>
<td>--------</td>
</tr>
<tr>
<td>LWP</td>
<td>$g_s$</td>
</tr>
<tr>
<td></td>
<td>$P_N$</td>
</tr>
<tr>
<td></td>
<td>ABA</td>
</tr>
<tr>
<td></td>
<td>Ca</td>
</tr>
<tr>
<td></td>
<td>Mg</td>
</tr>
<tr>
<td></td>
<td>K</td>
</tr>
<tr>
<td></td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>RWC</td>
</tr>
<tr>
<td></td>
<td>LER</td>
</tr>
<tr>
<td></td>
<td>TDM</td>
</tr>
<tr>
<td></td>
<td>FWR</td>
</tr>
<tr>
<td></td>
<td>TLA</td>
</tr>
<tr>
<td></td>
<td>TLA</td>
</tr>
<tr>
<td></td>
<td>SLA</td>
</tr>
<tr>
<td></td>
<td>OA</td>
</tr>
<tr>
<td></td>
<td>MPa</td>
</tr>
<tr>
<td></td>
<td>PRD</td>
</tr>
<tr>
<td></td>
<td>WW</td>
</tr>
<tr>
<td></td>
<td>NDI</td>
</tr>
<tr>
<td></td>
<td>DI</td>
</tr>
<tr>
<td></td>
<td>FC</td>
</tr>
<tr>
<td></td>
<td>SMC</td>
</tr>
<tr>
<td></td>
<td>IWUE</td>
</tr>
</tbody>
</table>