Managing the soil water balance of hot pepper (*Capsicum annuum* L.) to improve water productivity

by

Yibekal Alemayehu Abebe

Submitted in partial fulfilment of the requirements for the degree

Doctor of Philosophy in Horticultural Science

Department of Plant Production and Soil Science

In the Faculty of Natural and Agricultural Sciences

University of Pretoria

Pretoria

December 2009

Supervisor: Prof. J.M. Steyn

Co-supervisor: Prof. J.G. Annandale

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

DECLARATION

I, Yibekal Alemayehu Abebe declare that the thesis, which I hereby submit for the degree Doctor of Philosophy in Horticultural Science at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

SIGNATURE:_____________________

DATE: _____________________

DEDICATION

"This work is dedicated to my late father Alemayehu Abebe Kenne who inspired me to pursue higher learning and my wife Alem Sinshaw Belay and my son Abel Yibekal Alemayehu who sacrificed much due to my long absence."

PREFACE

This PhD thesis was prepared in the Department of Plant Production and Soil Science at the University of Pretoria, South Africa. The project involved two field trials, a rain-shelter trial and growth cabinet experiments at the Hatfield Experimental Farm, University of Pretoria. Data on soil and climate from five agro-ecological regions of Ethiopia were also used in the project. The main aim of this work was to assess management options and modelling approaches to designing management strategies to increase the water-use efficiency of hot pepper.

In Chapter 1, a brief introduction on hot pepper origin, ecology, deficit irrigation and irrigation scheduling was given. It also highlights the importance of careful selection of cultivars and plant populations for maximizing yield and the water-use efficiency (where water is limiting) of hot pepper. In Chapter 2, an elaborate literature review of the importance of water in plant production, and biological, agronomic, management and engineering means of improving water productivity in crop production were conducted. A detailed literature review was also done on the effects of different irrigation regimes on crop production in general and hot pepper production in particular. The role of varying plant populations on yield and quality of hot pepper was also reviewed.

In Chapter 3, effects of varying irrigation regimes on yield and water-use efficiency of hot pepper were investigated. In general, results from this study show that hot pepper is a water stress sensitive plant and frequent irrigation is crucial for optimum yield. The results also suggest that increasing the water-use efficiency by decreasing water application seems unattainable, as yield reduction is remarkably high due to decreased water supply.

In Chapter 4, effects of row spacing on yield and water-use efficiency of hot pepper were investigated. Generally, narrow row spacing significantly increased both yield and water-use efficiency of hot peppers. In Chapter 5, the combined effects of irrigation regimes and row spacing on yield and water-use efficiency of hot pepper were investigated. The results show that both high water supply and narrow row spacing increase yield. The water-use efficiency was also improved by narrow row spacing.

In Chapter 6, the agronomic and climatic data from the field experiments are utilized to determine FAO-type crop factors. This information is useful to schedule irrigation using the Soil Water Balance (SWB) and/or CROPWAT irrigation scheduling models. Similarly, in Chapter 7, field and climatic data collected are used to determine crop-specific growth model parameters for five hot pepper cultivars. This information is important to schedule irrigation using the SWB crop growth and other growth models. In both Chapters 6 and 7, attempts are made to create guidelines that help to estimate crop-specific model parameters from morphological features and maturity groupings of other hot pepper cultivars not included in this study.

In Chapter 8, attempts are made to determine cardinal temperatures: base, optimum, and cut-off temperatures for two hot pepper cultivars in studies conducted in the growth cabinet. It was very clear that cardinal temperatures for hot pepper cultivars in the vegetative and reproductive stages are markedly different.

In Chapter 9, the SWB model is calibrated and evaluated. The results show that most of the crop growth parameters considered was successfully simulated. The soil water deficit to field capacity was also simulated with sufficient accuracy to schedule irrigations. In Chapter 10, soil and climate data from five agro-ecological regions of Ethiopia are utilized to develop irrigation calendars and estimate water requirements of hot pepper cultivar Mareko Fana. Air temperatures, average wind speed and solar radiation appeared to influence the irrigation frequency, depth of irrigation and total water requirements.

In chapter 11, general conclusions and recommendations are provided. Furthermore, future research needs that have emanated from the present work are identified.

Four hot pepper cultivars (Jalapeno, Long Slim, Malaga, and Serrano) from South Africa and one (Mareko Fana) from Ethiopia were used in the study. The selection criteria used for the inclusion of these cultivars in this study were the diversity in terms of growth and fruit types they offered and their commercial importance.

The thesis is presented in article format. One article is published, while others were prepared for publication. The thesis is prepared in accordance with the guidelines for authors for the publication of manuscripts in the *South African Journal of Plant and Soil.*

ALEMAYEHU, Y.A., STEYN, J.M. & ANNANDALE, J.G., 2009. FAO-type crop factor determination for irrigation scheduling of hot pepper (*Capsicum annuum* L.) cultivars. *S. Afr. J. Plant Soil*. 26 (3), 186-194.

ALEMAYEHU, Y.A., STEYN, J.M. & ANNANDALE, J.G., 2009. SWB parameter determination and stability analysis under different irrigation regimes and row spacings of hot pepper (*Capsicum annuum* L) cultivars. (Prepared to be submitted for publication in the *South African Journal of Plant and Soil*).

ALEMAYEHU, Y.A., STEYN, J.M. & ANNANDALE, J.G., 2009. Calibration and validation of the SWB irrigation scheduling model for hot pepper (*Capsicum annuum* L.) cultivars for contrasting plant populations and soil water regimes. (Prepared to be submitted for publication in the *South African Journal of Plant and Soil*).

ALEMAYEHU, Y.A., STEYN, J.M. & ANNANDALE, J.G., 2009. Yield and water-use efficiency of hot pepper (*Capsicum annuum* L) as affected by irrigation regime and row spacing. (Prepared to be submitted to *New Zealand Journal of Crop and Horticultural Science*).

ALEMAYEHU, Y.A., STEYN, J.M. & ANNANDALE, J.G., 2009. Irrigation calendars and water requirements of hot pepper cultivar Mareko Fana in five agro-ecological regions of Ethiopia. (Prepared to be submitted for publication in the *East African Journal of Agriculture and Sciences*).

ACKNOWLEDGEMENTS

I would like to extend my deepest gratitude and thanks to my supervisors, Prof. J.M. Steyn and Prof. J.G. Annandale, for their encouragement, support, guidance, and constructive comments throughout the course of the studies. I am duly grateful to my supervisors for the financial assistance I received during the latter part of my studies.

Special thanks go to Haramaya University for sponsoring my study through the World Bank supported Agricultural Research Training Project (ARTP). I thank all the task force members of ARTP for their understanding and encouragement to finish this study.

I would like to acknowledge the support I received doing the experiments at the Hatfield Experimental Farm and would like to thank all the staff working there. I am deeply indebted to all my friends at the University of Pretoria and the Haramaya University whose support was indispensable in executing the field work, and whose friendly encouragement helped me to overcome the ups and downs that postgraduate studies demand.

I remain indebted to all my family members for their prayers, unstinting support and all-consuming love.

ABSTRACT

A series of field, rainshelter, growth cabinet and modelling studies were conducted to investigate hot pepper response to different irrigation regimes and row spacings; to generate crop-specific model parameters; and to calibrate and validate the Soil Water Balance (SWB) model. Soil, climate and management data of five hot pepper growing regions of Ethiopia were identified to develop irrigation calendars and estimate water requirements of hot pepper under different growing conditions.

High irrigation regimes increased fresh and dry fruit yield, fruit number, harvest index and top dry matter production. Yield loss could be prevented by irrigating at 20-25% depletion of plant available water, confirming the sensitivity of the crop to mild soil water stress. High plant density markedly increased fresh and dry fruit yield, water-use efficiency and dry matter production. Average fruit mass, succulence and specific leaf area were neither affected by row spacing nor by irrigation regimes. There were marked differences among the cultivars in fruit yields despite comparable top dry mass production. Average dry fruit mass, fruit number per plant and succulence were significantly affected by cultivar differences. The absence of interaction effects among cultivar and irrigation regimes, cultivars and row spacing, and irrigation regimes and row spacing for most parameters suggest that appropriate irrigation regimes and row spacing that maximize productivity of hot pepper can be devised across cultivars.

To facilitate irrigation scheduling, a simple canopy cover based procedure was used to determine FAO-type crop factors and growth periods for different growth stages of five hot pepper cultivars. Growth analysis was done to calculate crop-specific model parameters for the SWB model and the model was successfully calibrated and validated for five hot pepper cultivars under different irrigation regimes or row spacings. FAO basal crop coefficients (Kcb) and crop-specific model parameters for new hot pepper cultivars can now be estimated from the database, using canopy characteristics, day degrees to maturity and dry matter production.

Growth cabinet studies were used to determine cardinal temperatures, namely the base, optimum and cut-off temperatures for various developmental stages. Hot pepper cultivars were observed to require different cardinal temperatures for various developmental stages. Data on thermal time requirement for flowering and maturity between plants in growth cabinet and open field experiments matched closely. Simulated water requirements for hot pepper cultivar Mareko Fana production ranged between 517 mm at Melkassa and 775 mm at Alemaya. The simulated irrigation interval ranged between 9 days at Alemaya and 6 days at Bako, and the average irrigation amount per irrigation ranged between 27.9 mm at Bako and 35.0 mm at Zeway.

Key words: Basal crop coefficient, *Capsicum annuum*, cardinal temperature, model parameter, hot pepper, irrigation calendar, irrigation regimes, plant density, row spacing, Soil Water Balance model, water-use efficiency

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

ΔS	Change in soil water storage
Δt	Time step
°C d	Day degrees Celsius
°C	Degree Celsius
25D	Irrigation to field capacity at 20-25% depletion of plant available water
55D	Irrigation to field capacity at 50-55% depletion of plant available water
75D	Irrigation to field capacity at 70-75% depletion of plant available water
a_n	Leaf absorptance of near infrared radiation
a_p	Leaf absorptance of PAR
a_s	Leaf absorptance of solar radiation
CAI	Controlled alternative irrigation
CDM	Canopy dry matter
cm	Centimetre
CO_2	Carbon dioxide
CV	Coefficient of variation
D	Drainage
d	Willmott's index of agreement
DDF	Day degrees to 50% flowering
DDM	Day degrees to maturity
DM	Dry matter
DPAW	Depletion of plant available water
DWR	Vapour pressure deficit-corrected dry matter/water ratio
E	East

e_a	Actual vapour pressure
E_c	Radiation use efficiency
Eq.	Equation
e_s	Saturated vapour pressure
Es	Soil evaporation
E_{sim}	Simulated seasonal soil evaporation
E_{sTmax}	Saturated vapour pressure at maximum air temperature
E_{sTmin}	Saturated vapour pressure at minimum air temperature
ET	Evapotranspiration
ETc	Crop evapotranspiration
ET_{meas}	Measured seasonal evapotranspiration
ETo	FAO reference evapotranspiration
ET_{sim}	Simulated seasonal evapotranspiration
FAO	Food and agriculture Organization of the United Nations
FC	Field capacity
FI	Fractional canopy cover
FI_{PAR}	Fractional interception for PAR
FI_S	Fractional interception for total solar radiation
g	Gram
GDD	Growing day degrees
GLM	General linear model
H_2O	Water
ha	Hectare
Hc	Crop height

Hc_{max}	Maximum crop height
HDM	Harvestable dry matter
HI	Harvest index
I	Irrigation
K	Potassium
K_{bd}	Canopy radiation extinction coefficient for 'black' leaves
Kc	Crop coefficients
Kcb	Basal crop coefficients
Kc_{max}	The maximum value for Kc following rain or irrigation
Ke	Soil evaporation coefficient
kg	Kilogram
kPa	Kilopascal
K_{PAR}	Canopy radiation extinction coefficient for PAR
K_s	Canopy radiation extinction coefficient for total solar radiation
l	Litre
LAI	Leaf area index
LDM	Leaf dry matter
ln	Natural logarithm
LSD	Least square differences
m	Meter
m.a.s.l.	Meter above sea level
MAE	Mean absolute error
mg	Milligram

MJ	Mega joule
mm	millimeter
N	Nitrogen
n	Number of observation
NIR	Near infrared
NR	Narrow row
NS	Not significant
p	Leaf-stem partitioning parameter
P	Phosphorous
p	Probability level
Pa	Pascal
PAR	Photosynthetically active radiation
PAW	Plant available water
PE	Potential evaporation
PET	Potential evapotranspiration
PRD	Partial root zone drying
PT	Potential transpiration
PWP	Permanent wilting point
R	Runoff
r^2	Coefficient of determination
RCBD	Randomized complete block design
RDI	Regulated deficit irrigation
RD_{max}	Maximum rooting depth
RF	Precipitation (rainfall)

RH_{max}	Daily maximum relative humidity
RH_{min}	Daily minimum relative humidity
RMSE	Root mean square error
R_s	Daily total incident solar radiation
S	South
SDM	Stem dry matter
SE	Standard errors of means
SLA	Specific leaf area
SPAC	Soil-plant-atmosphere continuum
SWB	Soil Water Balance model
SWC	Soil water content
t	Ton
T	Transpiration
Ta_{max}	Maximum air temperature
Ta_{min}	Minimum air temperature
T_{avg}	Average air temperature
T_b	Base temperature
TDM	Top dry matter
TDMP	Top dry matter production
TE	Transpiration efficiency
T_m	Optimum temperature for crop growth
T_{max}	Maximum transpiration rate
T_{sim}	Simulated seasonal crop transpiration
T_x	Cut-off temperature

U	Wind speed
U_2	Mean daily wind speed at 2 m height
UN	United Nations
VPD	Vapour pressure deficit
WR	Wide row
WUE	Water-use efficiency
Y	Yield
μm	Micrometer
ψ_{lm}	Leaf water potential at maximum transpiration